



Supply Chain Management in Industrial Symbiosis Networks

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Publication date:
2016

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Citation (APA):

Herczeg, G., Akkerman, R., & Hauschild, M. Z. (2016). Supply Chain Management in Industrial Symbiosis Networks.

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Supply Chain Management in Industrial Symbiosis Networks



PhD thesis 3.2016

DTU Management Engineering

Gábor Herczeg
March 2016

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PhD thesis

Technical University of Denmark
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March 2016

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Preface

This dissertation contains research performed by the author from December 2011 to March 2016, submitted to DTU Management Engineering, Technical University of Denmark in fulfilment of the requirements for achieving a PhD degree. The research has been carried out at DTU Management Engineering and the TUM School of Management at the Technical University of Munich. The content consists of the latest versions of manuscripts of research papers to be submitted for publication. The project has been supervised by Professor Renzo Akkerman and Professor Michael Hauschild. The project was financed by DTU Management Engineering as part of their research program.

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Acknowledgments

I am thankful for all the support along the journey resulting in this thesis. Doing a PhD was indeed the longest challenge I have ever faced and I believe it had been much harder without the contribution and moral encouragement of my advocates, family, and friends.

My deepest gratitude is to my advisor Renzo Akkerman. His feedback and critique have been benchmark for my work. Our conversations trained my critical thinking and thought me to structure my thoughts as a scholar. His even-tempered nature and his advices helped me to overcome many crisis situations. I am glad that I can respect him as my advisor, colleague and friend. I am grateful to my co-advisor Michael Hauschild. His knowledge on sustainability and holistic approach have opened my perspective and fed into my ideas. Having him as advocate put me on an environmentally conscious path for which I am truly thankful. Furthermore, his patient and kind supervision was always appreciated. I am deeply grateful to both of my advisors for their trust; they had been inspiring and catalyzing my work.

I am honoured for the opportunity of earning PhD degree at the Technical University of Denmark and also being a research associate at the Technical University of Munich. I would like to thank to my colleagues at both institutions for the friendly and collaborative environment we produced. Special thanks to my fellow researchers, Martin, Samuel, Christian, Radu and Jishna in Lyngby and Munich for making work enjoyable and productive. I am thankful for Christina Scheel Persson for coordinating the administrative process of my PhD project.

I am sincerely thankful to my family for sharing the ups and downs that accompanied this journey. I am truly grateful to my wife Virág who had been my partner for the three years I spent in Denmark and ever since. Her consistent encouragement and spiritual support were absolutely necessary; her love is always a source of peace. I am thankful to my parents for encouraging me to pursue work that I love, motivating me to go abroad, and supporting my studies. In Hungary, my family provided me with a relaxed environment where I was able to return and recharge, find inspiration, and always remember where home is. Also, I am thankful to my friends Nazim and Miguel who made life in Copenhagen joyful, intellectually profound, and culturally vibrant.

Summary

Sustainable supply chain management deals with the design and operation of profitable supply chains that also respect limitations on natural resources, do no harm to the environment, and consider the social systems they operate in. In academic research on sustainable supply chain management, as well as in policy documents from e.g. the European Union, the concepts of circular economy and closed-loop supply chains have received significant attention. One of the manifestations of these developments are industrial symbiosis networks. These networks are a collaborative effort to more sustainable production operations, and are characterized by a supply chain reconfiguration that uses one company's wastes or by-products as a raw material for another company, avoiding waste disposal while also reducing material requirements. The resulting networks of relationships contribute to regional sustainable development efforts, and emphasize synergistic relations, community, and collaboration.

This thesis takes an operations and supply chain management perspective on industrial symbiosis networks. More specifically, the thesis elaborates on the collaborative and competitive characteristics of industrial symbiosis. First, it discusses the supply chain integration and coordination challenges that appear in industrial symbiosis, on both an organizational and operational level. Secondly, the thesis discusses the organizational capabilities and resources relevant for the competitiveness of industrial symbiosis networks on three dimensions: the level of the firm, the network, and the business environment. Finally, the thesis elaborates on supply chain resiliency based on a formal model with multiple concurrent suppliers. The model includes fairness considerations in different by-product allocation strategies, which turn out to have different requirements and consequences for the organization and facilitation of the collaborative efforts.

Overall, this thesis aims to ground industrial symbiosis in operations and supply chain management theory. The thesis thereby provides a basis for the improved organization and operation of industrial symbiosis networks, and supports the development towards resource-efficient closed-loop material flows.

Resumé

Bæredygtighed i supply chain management handler om at udvikle og at styre forsyningskæder som er ikke kun profitabelt, men også respekterer begrænsninger i ressourcer, skåner miljøet, og respekterer den sociale sammenhæng forsyningskæden opererer i. I supply chain management forskningen, og også i miljøpolitiske diskussioner i f.eks. Danmark eller Den Europæiske Union, har begreberne cirkulær økonomi og lukkede kredsløber fået betydelig opmærksomhed. Et af de mest kendte eksempler i denne udvikling er industrielle symbiosenetværk, en slags industrielle kosystemer, hvor flere virksomheder samarbejder for at få en mere bæredygtig produktion. Symbiosenetværk er baseret på en opsætning af forsyningskæder, hvor én virksomheds affaldsprodukter eller biprodukter bliver til en ressource for en anden virksomhed. På den måde undgår virksomheder omkostninger ved bortskaffning af affaldsprodukter og samtidig realiseres besparelser på ressourcesiden. Samarbejdet i symbiosenetværk bidrager til en bæredygtig udvikling af lokal området, og understøtter synergi, godt naboskab og samarbejde.

Denne afhandling beskæftiger sig med et supply chain management perspektiv på industrielle symbiosenetværk. Den uddyber de kollektive og konkurrencedygtige karakteristika ved symbiosenetværk. Afhandlingen diskuterer udfordringer i forhold til integration og koordination af forsyningskæder i symbiosenetværk, hvor både organisatoriske og operationelle aspekter bliver behandlet. Til at uddybe konkurrencedygtighed ved symbiosenetværk, diskuterer afhandlingen også de organisatoriske kapaciteter og ressourcer som virksomheder bruger til at opnå konkurrencedygtigheden. Disse kapaciteter og ressourcer bliver identificeret på tre niveauer: virksomhed, netværk, og erhvervsklima. Til sidst diskuterer afhandlingen supply chain resiliency baseret på en model, som inkluderer flere samtidige leverandører af affaldsprodukter eller biprodukter. Modellen fokuserer på at betragte retfærdigheden i forskellige metoder til allokeringen af produkterne. Resultaterne viser, at de forskellige metoder også fører til forskellige krav og konsekvenser med hensyn til organisering og facilitering af samarbejdet.

Afhandlingens overordnede mål er at udvikle et fundament til industrielle symbioser inden for supply chain management teori. Afhandlingen konstruerer dermed et grundlag for bedre organisation og drift af industrielle symbiosenetværk og hjælper virksomheder og andre interessenter til at øge ressourceeffektiviteten og støtte dem i omstillingen til en cirkulær økonomi.

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CHAPTER 1

Introduction

Sustainability of economic development has been in the centre of interest of political and business grounds since the book *Our Common Future*, also known as the Brundtland Report, was published in 1987. In this report, the World Commission on Environment and Development defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). Although the definition has been criticised for its all encompassing scope, as a result the sustainability movement gained momentum.

Today, the European Union has a vision of “living well within the limits of the planet” (EU 2013). However, Europe faces both persistent and emerging challenges in the realization of this vision (EEA 2015). Production and consumption in today’s industrial society depletes non-renewable resources and generates waste at an unprecedented rate and on global scale. This not only creates challenges for future generations, but already for the communities we live in. It is now clear that to address concerns relating to the security of access to natural resources and the wider environmental impacts of escalating global resource use, a sustainable industrial society has to emphasise resource efficiency through a closed-loop system of materials (EEA 2016).

1.1 Sustainable supply chain management

In general, a supply chain encompasses every effort involved in producing and delivering a product from the supplier to the final customer. Furthermore, supply chain management focuses on multiple customer-supplier dyads ulti-

mately spanning from raw material extractors to the final customer (Harland 1996). The theory of supply chain management is grounded on a paradigm of cooperative strategic management that emphasizes collaboration within a network of interdependent relationships with the goal of deriving mutual benefits (Chen and Paulraj 2004). The theory draws on the “relational view” of inter-organizational competitive advantage (Dyer and Singh 1998) and typically considers the dyad or the network as the unit of analysis.

Sustainability concerns caused a movement towards triple bottom line performance measures concerning the relationship of profit, people, and the planet (Elkington 1998). The triple bottom line has been applied to supply chain management resulting in challenges related to e.g. environmental impacts, health and safety concerns, and employment issues (Kleindorfer et al. 2005). Kleindorfer et al. argue that to find opportunities for obtaining competitive advantage while also meeting environmental and social needs, supply chain management needs strategies that re-evaluate material choices and pursue closed-loop supply chains and safe disposal. Furthermore, companies need to develop capabilities in operations and supply chain management for long-term sustainability.

The fact that the supply chain causes emissions in and places a burden on the natural environment has been long recognized (Bloemhof-Ruwaard et al. 1995). In general, the supply chain’s need for natural resources extracts non-renewable and scarce resources from the planet. Furthermore, emissions and wastes that are generated along the supply chain are transported and transformed and result in water, air and soil pollution with damaging effects on the environment. These concerns have been translated into an environmentally responsible supply chain management.

However, sustainable development also entails corporate social responsibility (Holme and Watts 1999). According to Holme and Watts, corporate social responsibility is the continuing commitment by business to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families as well as of the local community and society at large. In general, supply chains employ workers to produce and distribute products to consumers. Furthermore, people’s health and safety are affected by these products and the environmental impact that supply chains generate. Consequently, sustainable supply chain management must also extend to the people domain (Tang and Zhou 2012).

In general, improving the sustainability of supply chain operations is affected by policy rooted in natural and social sciences (Linton et al. 2007). However, research and practice in supply chain management can also af-

fect policy and science by presenting alternative scenarios for the development of sustainable supply chains. Sustainability stretches the concept of supply chain management including the entire production system and post-production stewardship (Linton et al. 2007). Furthermore, sustainable supply chain management must also integrate organizational, governmental, and community stakeholder perspectives into the business perspectives (Seuring and Müller 2008). Most importantly, however, research and practice has to overcome making unsustainable supply chains less unsustainable. In other words, truly sustainable supply chains must not cause environmental or social harm (Pagell and Shevchenko 2014).

In research on sustainable supply chain management, the concept of closed-loop supply chains has received significant attention. Here, the term closed-loop supply chain refers to system in which materials and products are in circulation as a opposed to a linear extraction, production, consumption, disposal system. Traditionally, closed-loop supply chains take care of product recovery after consumer use (Fleischmann et al. 2000). Closed-loop supply chain management considers the product life-cycle including its design and recovery in order to maximize value creation (Guide and van Wassenhove 2006). The closed-loop supply chain encompasses a forward channel and a reverse channel, which includes the collection of end-of-life products and recycling activities. There is a significant amount of research on various aspects of closed-loop supply chains and reverse logistics, as well as many directions for future research (Govindan et al. 2015). However, supply chains also generate undesired outputs upstream. Managing manufacturing by-products are a distinct part of sustainable supply chain management apart from product recovery (Linton et al. 2007).

Sustainable supply chain management must be explicitly extended to include undesired outputs generated along the supply chain, to consider the entire lifecycle of products, and to optimize a product from a total costs standpoint (Linton et al. 2007). Total costs must include the effects of resource depletion and the generation of undesired outputs that are neither captured nor used. According to Linton et al. (2007), the challenges require management to change existing practices and create new production and management systems. In other words, management has to reconceptualize what the supply chain does from a business point of view, who is involved in the supply chain, and how the performance of this supply chain is measured (Pagell and Wu 2009).

With respect to the loop-closing effort of supply chain management, industrial ecology has been pointed out as a source of useful insights on the

efficient and productive use of by-products and wastes generated along the supply chain (Kleindorfer et al. 2005, Linton et al. 2007). Furthermore, Linton and his colleagues refer to the concept of industrial ecosystems as a manufacturing and supply chain strategy.

1.2 Industrial ecosystems and industrial symbiosis

The Brundtland Report on sustainable development gave momentum to new ideas concerning challenges around sustainability. Although there had been earlier attempts to realise closed-loop material flows, the idea became popular thanks to an article published in 1989 by Robert Frosch and Nicholas Gallopoulos in the magazine *Scientific American* in a special issue on “Managing Planet Earth”. The authors introduced the concept of industrial ecosystems to a large audience, which was a significant development for the emerging field of industrial ecology (Erkman 1997).

Frosch and Gallopoulos (1989) conceptualised an ideal industrial ecosystem where the consumption of materials and energy is optimised, waste generation is minimized and the undesired outputs of one production or consumption process serve as the raw material input for another process. They argued that processes are required to minimize the generation of unrecyclable wastes as well as minimize the consumption of scarce material and energy resources. Furthermore, they pointed out that individual production processes cannot be considered in isolation; linking inputs and outputs of individual processes is crucial for building a closed system.

In general, industrial ecology offers a design and policy framework for industrial ecosystems (Ehrenfeld 1997). According to Ehrenfeld design encompasses activities to establish new forms of technology, organizational (institutional) structures, human competences and regulations that help to achieve the desired changes. Furthermore, he emphasizes that the design process must be bottom-up, participatory, rooted in practical experience, and arising from the understanding of those most centrally involved. The design principles include reducing energy consumption while emphasising renewable energy sources, keeping substances that upset natural processes out of the environment, dematerialising industrial output¹, and creating loop-closing industrial ecosystems with circular material flows.

Industrial ecology recognises the limits of cleaner production and pollution prevention arguing that most production and consumption processes

¹Dematerialisation essentially aims to reduce material consumption of products. It led to trends, for example in decreasing product weight and product services.

necessarily generate undesired outputs, such as wastes and by-products (Erkman 1997). Given these practical limits, and to achieve a more efficient use of resources, the loop-closing aspect of industrial ecology suggests an integrated view on production processes within a larger system (Ehrenfeld 1997). The integrated and systematic view on interrelated production and consumption processes draws boundaries around industrial ecosystems. These boundaries are either geographical (e.g. within a region or industrial district) or based on the product/material chain (Boons and Baas 1997).

In general, loop-closing efforts result in recycling structures. Schwarz and Steininger (1997) describe recycling structures by system elements (companies) and “waste relationships” that connect two or more elements by waste flows and information flows. Furthermore, they argue that quantitative changes in the surrounding system (e.g. increase in waste disposal fees, development of environmental scarcities) may trigger a network level organization of system elements with common waste-related goals. The resulting recycling network is characterised by long-term collaboration between companies emphasising stable relationships and strategic information exchange. However, the size of the recycling network is limited by organizational, informational, economic, regulatory and technical constraints that typically allow development within geographical boundaries.

The first recycling network in history to be uncovered by researchers is the Kalundborg Industrial Symbiosis in the northern part of Sjælland in Denmark (Ehrenfeld and Gertler 1997). In general, the term “symbiosis” is used to describe the mutual aspect of relationships that provides collective economic benefits to the participants². In Kalundborg, industrial symbiosis involves eight public and private companies that buy and sell wastes and by-products, and has been emphasizing collaboration for more than fifty years (Symbiosis Institute 2016). Figure 1.1 depicts the supply network. The resulting advantages for the whole region lie in the companies’ economic benefits, the indirect contribution to regional development, and in the reduction of the total emission and disposal released by the system (Jacobsen and Anderberg 2004).

Since it was first coined, the term “industrial symbiosis” has become established within the field of industrial ecology and also within the business community and with policy makers. In the last two decades, the term was used to describe recycling activities in regional districts and eco-industrial parks (for a compilation of projects worldwide see Massard et al. (2012)), as well as large scale recycling initiatives, such as the National and Global Industrial

²Symbiosis is a biological metaphor referring to a close sustained living together of two species or kinds of organisms.

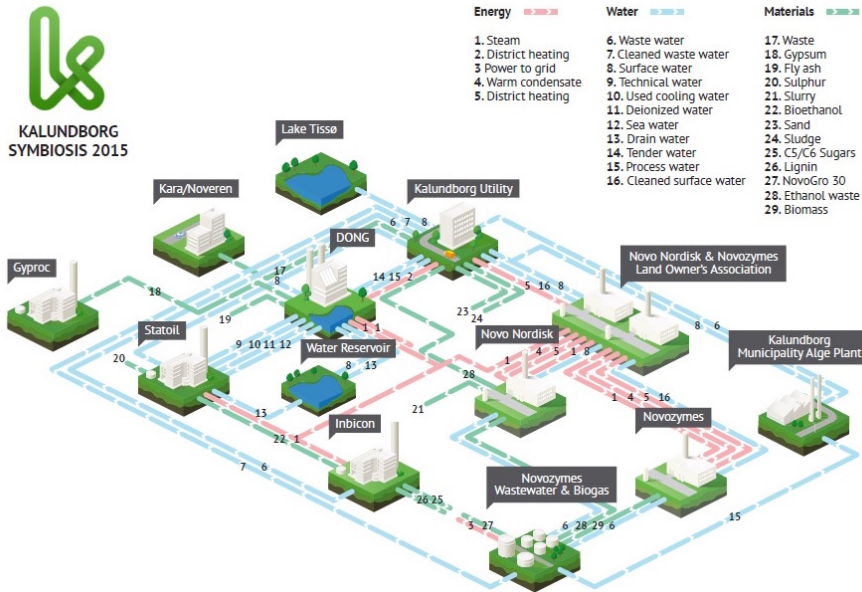


Figure 1.1: The industrial symbiosis in Kalundborg, Denmark (Symbiosis Institute 2016).

Symbiosis Programme (International Synergies 2016). Industrial symbiosis is identified as a key feature of industrial ecosystems. Furthermore, according to the European Environmental Agency, industrial symbiosis is a key enabling factor for resource efficiency (EEA 2016).

By definition, industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products (Chertow 2000). Consequently, virgin raw materials are substituted by undesired production outputs. However, the development of industrial symbiosis is different from common market activities. Researchers argue that industrial symbiosis requires geographical proximity, institutionalization of shared values, regulatory context, and high information flows (Ehrenfeld and Gertler 1997, Schwarz and Steininger 1997). Furthermore, industrial symbiosis networks develop gradually through an evolutionary process. In order to progress from the stage of waste relationships, participants must be aware of their positive environmental externalities and institutionalize industrial symbiosis, including the embeddedness of network actors, the role of locational factors, and the ways in which social capital comes into play (Chertow and Ehrenfeld 2012). During its evolution, industrial symbiosis engages diverse organizations in

a network to share and create knowledge fostering eco-innovation and long-term cultural change (Lombardi and Laybourn 2012)

1.3 Managing industrial symbiosis networks

The managerial implications of industrial ecology were first emphasised in 1993 by the British consultant Hardin Tibbs (Erkman 1997). According to Tibbs, the framework of industrial ecology is uniquely able to provide the co-ordinating vision for corporate environmental strategy (Tibbs 1993). Furthermore, industrial ecology permits an integrated technological and managerial interpretation, including business application and technological opportunity domains. However, From a business point of view, the challenge for industrial ecology is to offer an agenda that allows progress to be measured, enhanced business performance, and applicability by any industry, permitting alliances and cooperation among companies and between industries.

Industrial symbiosis is a collaborative business approach to increase resource efficiency (EEA 2016). Organizations in industrial symbiosis networks translate the principles of industrial ecology into practical business applications. They emphasize loop-closing efforts resulting in synergistic inter-organizational relationships. Most importantly, the resulting mutual cost reduction, increased revenues, and competitive advantages cause synergies to be attractive business opportunities.

In general, the performance of an industrial symbiosis network can be benchmarked against an industrial system that operates without symbiosis (van Berkel 2010). The benefits can then be measured by the substitution of virgin material intake and the avoidance of waste disposal. Furthermore, the conversion of undesired outputs may be positive for technological innovation and employment even though it requires facilities, staff, and energy. Ideally, industrial symbiosis also improves energy efficiency and increases the amount of process outputs that have market value (Lowe 1997). Furthermore, industrial symbiosis not only reduces undesired production outputs, but the tight network of inter-organizational relationships fosters social equity and economic prosperity. In other words, industrial symbiosis is aligned with the triple bottom line of sustainability.

Industrial symbiosis networks have however also been criticised for the potential environmental risks they entail. Lowe (1997) argues that focusing on industrial symbiosis could lock in continued reliance on unsustainable technologies and toxic materials, thereby overlooking other industrial ecology principles. The short-term benefits in industrial symbiosis networks can

delay innovation in terms of clean technologies. In other words, resource efficiency improvements achieved with synergies have to be considered within a larger context of effective environmental solutions that look into the future.

Companies in industrial symbiosis networks must have an environmentally proactive strategic stance combining life-cycle thinking and a long-term view, and welcome cooperation and alliances with other organizations (Tibbs 1993). Achieving industrial ecology objectives requires the management of relations between the organizations involved (Boons and Baas 1997). With respect to the evolutionary aspect of industrial symbiosis networks the aim of management is to initiate synergistic relations and to support their progression towards an integrated network pursuing the principles of industrial ecology. Based on empirical evidence, Chertow and Ehrenfeld (2012) argue that industrial symbiosis networks that persist move into the direction of environmental sustainability. Furthermore, the key factors in their development include a broader view of economic analysis that includes local and regional variables, a bottom-up cooperation model across companies, and revealed and quantified environmental benefits.

In general, there are two types of management approaches in relation to industrial symbiosis networks. Industrial symbiosis is often a self-organizing system, in which individual companies spontaneously start cooperation and build alliance partnerships (Chertow and Ehrenfeld 2012). Furthermore, there can also be the involvement of a support system – an organizational unit – that facilitates the development of industrial symbiosis networks (Lowe 1997). However, development models that have a top-down approach with a central plan for cooperation have proven to be less successful, particularly in Europe and North America (Heeres et al. 2004, Gibbs and Deutz 2007). Chertow and Ehrenfeld (2012) explain their failure with lack of embeddedness and institutionalization that would foster and disperse the norms of cooperation inherent to industrial symbiosis.

The spontaneous organization of industrial networks draws on the social network of companies (Ashton 2008). Ashton finds that trust among managers and position in the social hierarchy is correlated with industrial symbiosis. Furthermore, there is consensus about that institutionalization of industrial symbiosis may only manifest if there is a fundamental sense of community among businesses (Ehrenfeld 1997, Ashton 2008, Chertow and Ehrenfeld 2012). Conversely, a lack of such community and cohesion hinders the evolution of industrial symbiosis networks because there is no social network on which it can be built (Boons and Baas 1997).

While industrial symbiosis networks must be largely self-organizing, there

is a significant role for an organizing team and an organizational unit (Ehrenfeld 1997, Chertow and Ehrenfeld 2012). According to Ehrenfeld the basic responsibility of an organizing team is to support companies in exploring feasible synergistic opportunities with other companies with guidance and information. Furthermore, a broker (coordinator) may take the responsibility for maintaining the cohesion of a broader network as well as for sales and marketing of wastes and by-products. The broker would help companies to perceive their common opportunities and explore opportunities for increasing effectiveness of the whole network (Ehrenfeld 1997). The National Industrial Symbiosis Programme in the United Kingdom is for example facilitated by a group of experts that aim to engage companies in spontaneous collaboration, and also try to increase the effectiveness of existing well-performing symbioses (Paquin and Howard-Grenville 2012).

The key role of the organizational unit is to institutionalize industrial symbiosis (Chertow and Ehrenfeld 2012). In general, the organizational unit provides a platform where companies can meet each other, share information about their undesired production outputs, and conceptualize ideas concerning synergies. Furthermore, the organizational unit offers a platform where companies and authorities can interact. Consequently, companies become informed about regulations concerning waste reuse and can in turn influence regulatory policy. The Symbiosis Institute is the organizational unit of the industrial symbiosis in Kalundborg. The Symbiosis Institute evolved along with the network and is now partially responsible for the development of the network: its core aim is to align industrial cooperation and regional sustainable development efforts, involving both competitive industry and a responsible and efficient use of natural resources (Jacobsen and Anderberg 2004).

In industrial symbiosis networks, organizational relations manifest synergistic transactions (by-product synergies), involving by-product sellers and buyers (Lowe 1997). Transaction costs typically include partner search costs, the cost of negotiating the terms of the exchange, and the cost of enforcing the resulting contracts (Chertow and Ehrenfeld 2012). Furthermore, industrial symbiosis creates inter-dependency between the partners (Boons and Baas 1997). This inter-dependency results from the fact that organizations do not control all the resources necessary for their activities. In fact, in synergistic transactions, supply and demand of by-products are a function of independent market mechanisms. However, inter-dependency in industrial symbiosis is managed in a cooperative manner, manifesting strategic alliances (Boons and Baas 1997). Consequently, supply chain management is relevant in industrial symbiosis networks.

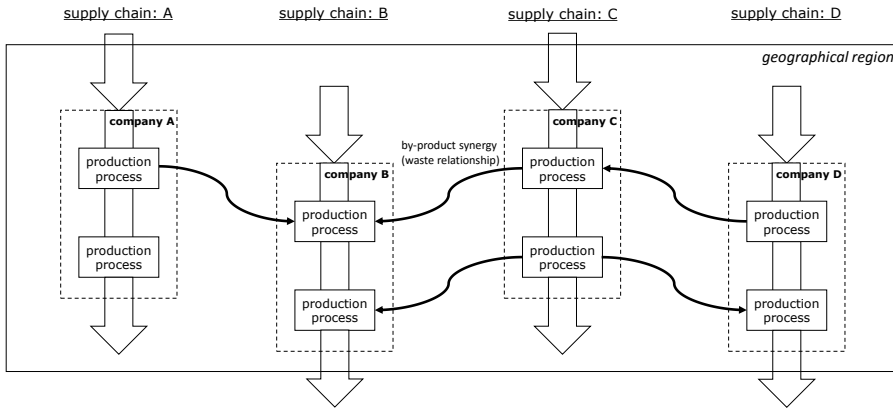


Figure 1.2: Illustration of material flows in industrial symbiosis networks within geographical boundaries

However, industrial symbiosis networks are different from traditional supply chains in several aspects (Bansal and McKnight 2009). First, the architecture of the two supply systems is different. According to Bansal and McKnight (2009), while the emphasis of traditional supply chain management is waste reduction within a company, the emphasis of industrial symbiosis is waste reduction over an entire system of companies. They point out that, in addition to forward and reverse flows, in industrial symbiosis networks, wastes and by-products create a “sideways” flow of products, as illustrated in Figure 1.2. In other words, industrial symbiosis manifests across supply chains. Furthermore, from a business point of view, synergistic relationships take advantage of idiosyncratic fit between firms based on by-product supply and demand within geographical boundaries.

Second, a key difference between industrial symbiosis and traditional supply chains is reflected in the coordination mechanisms (Bansal and McKnight 2009). Symbiotic partners typically have “short mental distance” and a shared vision to emphasize local environmental and social sustainability (Jacobsen and Anderberg 2004). In general, these conditions allow the translation of industrial ecology principles into business applications (Tibbs 1993). Furthermore, communication and personal relationships are important parts of network emergence and formulating the sustainability vision. In addition, trust is an important coordination mechanism in determining the companies’ engagement with the industrial symbiosis network (Lombardi and Laybourn 2012). In industrial symbiosis, companies need to trust their partners to meet quality and quantity expectations in relation to the exchanged by-products (Bansal and McKnight 2009).

In general, the supply and demand of by-products and waste creates challenges and risks for industrial symbiosis (Lowe 1997). Stability of by-product supply is considered as the “Achilles heel” of industrial symbiosis (Côté and Smolenaars 1997). Similarly, demand security is also an important factor (Jacobsen and Anderberg 2004). However, the quantity of by-products (both supply and demand) is determined by the demand for the core products, and because production operations are normally driven by the core product, the quality of by-products can be compromised (Bansal and McKnight 2009). Consequently, synergistic transactions carry liability. There is a risk of losing a critical supply or market if a plant closes down or changes its product mix (Lowe 1997). In addition, an uneven quality of by-products could damage the equipment or the quality of products. To coordinate cooperation, companies typically rely on standard mechanisms like long-term agreements, bilateral contracts, and joint-ventures (Jacobsen 2006).

If industrial symbiosis creates too much inter-dependency among the companies, the failure of one or few critical links could damage the performance of the whole network (Lowe 1997). This kind of fragility of industrial symbiosis networks has been pointed out by others as well (e.g. Côté and Smolenaars 1997, Zhu and Côté 2004, Bansal and McKnight 2009). Consequently, Lowe (1997) argues that maintaining alternative suppliers and customers creates redundancy and a broader market, which will give greater resilience to the pattern of trades. Furthermore, increasing diversity in a by-product portfolio helps to manage temporary production or marketing problems: losses from a by-product line can be compensated by profits of other lines (Zhu and Côté 2004). However, the emerging challenge with greater resilience, which comes from increased redundancy and/or diversity, is to ensure consensus among participants regarding mutual benefits (Lowe 1997).

1.4 Research gaps

Industrial symbiosis has been studied for about two decades. The related research domain is growing in breadth and is increasing the pace of integration between natural and social sciences (Lombardi et al. 2012). Analyzing the trend in industrial symbiosis research, Yu et al. (2013) concluded that mainstream research can be divided into five disciplines: (i) wastewater treatment and management, (ii) energy efficiency, (iii) solid waste management, (iv) self-organization of industrial symbiosis networks, and (v) policy making and evaluation for industrial symbiosis and eco-industrial park projects. Furthermore, their analysis identified that industrial symbiosis is loosely and

indirectly connected with research areas such as supply chain management.

Indeed, the idea of industrial ecosystems presented by Frosch and Gallopoulos (1989) penetrated to the discipline of sustainable supply chain management (Linton et al. 2007). However, research within the supply chain management discipline concerning industrial symbiosis has not been proliferated yet. Nevertheless, it has been found that sustainable (green) supply chain management takes advantage of industrial symbiosis, and it has been suggested that supply chain integration should begin to form networks instead of following the path of a single product (Zhu and Côté 2004). Furthermore, in comparison with traditional supply chains, industrial symbiosis networks have complex coordination mechanisms combining market mechanisms with community relationships, trust, and a shared sustainability vision (Bansal and McKnight 2009).

Currently, the domain of industrial symbiosis constitutes a niche within supply chain management research. However, as far as policy is concerned, industrial symbiosis is declared as a central tool in closing resource loops (EC 2015, EEA 2016). Clearly, management has a pivotal role in translating industrial symbiosis into practical business application (Tibbs 1993, Erkman 1997). Furthermore, supply chain management has the scope that comprehends the collaborative, inter-organizational aspects of industrial symbiosis networks. Consequently, there is an opportunity for supply chain management research to make important contributions in relation to industrial symbiosis.

In general, there are several facets of the industrial symbiosis phenomenon where supply chain management can contribute. First, the collaborative feature of industrial symbiosis is particularly interesting. Collaboration in industrial symbiosis networks emphasizes relations across supply chains instead of along the supply chain, and it entails community and business relationships in geographical proximity instead of buying and selling globally. This collaborative effort, however, needs to overcome challenges in order to successfully translate industrial symbiosis into a business application that is in line with the triple bottom line considerations. Supply chain management theory can be used to elaborate on the relevant aspects of collaboration to identify challenges in managing industrial symbiosis networks in particular. Filling this research gap will be beneficial in understanding the sustainability performance of industrial symbiosis networks, and provide directions to increase their feasibility and resource efficiency. This research gap translates into the following research questions (*RQ*):

RQ1a — How do companies in industrial symbiosis pursue the triple bottom line of sustainability?

RQ1b — What are the supply chain collaboration challenges that affect the sustainability performance of industrial symbiosis networks?

Second, the competitiveness feature of industrial symbiosis is also interesting. In fact, collective competitive advantage is what makes synergistic opportunities attractive for companies (Chertow 2000). From a managerial point of view, competitive advantage requires an idiosyncratic value creation strategy that is not simultaneously being implemented by other competitors (Barney 1991). It is widely accepted that industrial symbiosis increases natural resource productivity (Porter and van der Linde 1995, Esty and Porter 1998). Furthermore, competitiveness includes reduced costs through innovative product and process changes, increasing revenue, diversifying business, and managerial risk (Lombardi and Laybourn 2012). However, there is a research gap regarding the idiosyncratic features of industrial symbiosis. Supply chain management theory and strategic management theory can be used to identify the key components of collective competitive advantage in industrial symbiosis. Filling this gap has important practical implications regarding implementing industrial symbiosis as part of the loop-closing strategy. Furthermore, filling this gap will also contribute to supply chain management theory because it comprehends the inter-organizational competitive features of industrial symbiosis networks. The following questions are put forward:

RQ2a — What are the key capabilities and resources that firms participating in industrial symbiosis rely on?

RQ2b — How is competitive advantage in industrial symbiosis networks obtained based on these capabilities and resources?

Finally, the combination of the collaborative and competitiveness features also provides opportunities for research. In particular, the management of trade-offs when economic profitability is combined with an extended stakeholder view is interesting. In fact, mutually beneficial relations are one of the hallmarks of industrial symbiosis (Chertow 2000). Managing industrial symbiosis networks may involve multiple, concurrent suppliers and/or buyers to increase supply chain resilience while ensuring collective benefits (Lowe 1997). However, these benefits have to be allocated to often non-equally performing participants. Providing a fair distribution of benefits implies an economic trade-off because it can imply a sub-optimal allocation of resources. Consequently, it is important to quantify the “price of fairness” in industrial symbiosis networks that comes with multiple, concurrent by-product suppliers or buyers. In general, there is a research gap regarding the notion of fairness in relation to industrial symbiosis. Filling this gap requires the develop-

ment of a fairness measure and the proposition of fair allocation strategies in industrial symbiosis networks. Furthermore, elaborating on the idea of fairness in this context also contributes to the supply chain management literature. The following research questions are proposed:

RQ3a — How can the price of fairness be measured in industrial symbiosis networks?

RQ3b — How do different fairness approaches influence collaboration in industrial symbiosis networks?

1.5 Thesis outline

This thesis approaches industrial symbiosis from a supply chain management aspect. The purpose is to contribute to research on sustainable supply chain management by grounding industrial symbiosis networks in management theory. Furthermore, the aim is to offer a common ground for business and action being proposed by policy concerned with resource efficient closed-loop material flows. To do so, the thesis elaborates on the collaborative and competitiveness features of industrial symbiosis networks.

The thesis includes three main chapters that each address one of the identified research gaps and corresponding research questions. Note that the individual chapters are based on manuscripts of papers to be submitted for publications, and therefore might cause some minor overlap in introductory content to make sure the papers are self-sufficient.

In Chapter 2, a theoretical framework is built and used to discuss how industrial symbiosis pursues sustainability and to identify the main collaboration challenges and performance impacts. The analysis is supported by selected published case studies of industrial symbiosis networks. The chapter identifies organizational and operational challenges for collaboration in the context of IS networks, related to integration and coordination of supply chain activities.

In Chapter 3, the competitive advantage attributed to industrial symbiosis is grounded in the resource-based theory, which is a widely accepted theory of competitiveness. Here again, the analysis is supported by selected published case studies. The chapter identifies the key capabilities and resources that managers leverage in industrial symbiosis networks. Furthermore, the chapter elaborates on how competitive advantage can be obtained using these capabilities and resources during the initiation and progression of industrial symbiosis networks.

In Chapter 4, the notion of fairness is introduced to industrial symbiosis. A mathematical model of an industrial symbiosis network with multiple, concurrent suppliers is developed to measure the economic efficiency of resource allocation. Furthermore, fair resource allocation strategies are proposed and compared based on their resulting efficiency trade-offs. The findings show that the “price of fairness” of the allocation strategies is different and depends on the general supply-demand of by-products. Furthermore, the chapter elaborates on how the allocation strategies support, collaborative, individualistic or even altruistic behaviour in industrial symbiosis networks.

Finally, in Chapter 5 the thesis contains a conclusions chapter that summarizes the findings and outlines future research opportunities on supply chain management in industrial symbiosis networks.

CHAPTER 2

Collaborative effort for sustainability

This chapter is based on a manuscript to be submitted for publication under the title “Supply chain collaboration in industrial symbiosis networks”. The manuscript is co-authored by Gábor Herczeg, Renzo Akkerman and Michael Zwicky Hauschild.

Abstract

One of the central strategies supporting the development of a circular economy, industrial symbiosis, is a form of collaborative supply chain management aiming to make industry more environmentally sustainable and achieve collective benefits based on utilization of waste, by-products, and excess utilities between economically independent industries. This paper investigates industrial symbiosis from a supply chain collaboration perspective. A theoretical framework is built and used to discuss how industrial symbiosis pursues sustainability and to identify the main collaboration challenges and performance impacts. The analysis is supported by selected published cases. The paper identifies organizational and operational challenges for collaboration in the context of industrial symbiosis networks, related to integration and coordination of supply chain activities. As industrial symbiosis has only received little attention in the operations and supply chain management community, the identified challenges directly lead to future research directions for this community. The analysis in this paper provides directions to increase the feasibility and resource efficiency of industrial symbiosis networks and can hence be used by stakeholders involved in these networks. industrial symbiosis is a central element in the development of circular economy and is therefore increasingly used in efforts to strengthen industry’s resource efficiency. The resulting collaborative supply chains have however received limited attention. This paper aims to provide a supply chain collaboration perspective and thereby contribute to an increased and more systematic understanding of industrial symbiosis.

2.1 Introduction

Industrial symbiosis is a concept based on the idea of industrial ecosystems, establishing symbiotic relationships between traditionally different and economically independent industries, typically in a relatively close geographical proximity (Chertow 2000). An industrial ecosystem refers to the idea of reusing waste from one industrial process in another industrial process. In such industrial ecosystems, the consumption of materials and energy is optimized, and by-products from one industry serve as raw materials for other industries, reducing the disposal of waste and loss of resources (Frosch and Gallopoulos 1989).

Building on the obvious economic benefits of sharing waste streams and by-products, industrial symbiosis aims to improve environmental performance and social responsibility (Mirata 2004, Bansal and McKnight 2009). Economically, participating companies benefit by gaining access to cheaper sourcing and/or by avoiding disposal costs. Environmentally, the benefits are reduced natural resource consumption and waste disposal and reduction of emissions to air, water and soil from the production of the saved raw materials (e.g. Schwarz and Steininger 1997, Chertow and Lombardi 2005, Jacobsen 2006). Finally, from a social perspective, participating in industrial symbiosis emphasizes the local community, working cooperatively with other industries and governmental bodies to contribute to regional economic development (Baas and Boons 2004)). As such, the ideas behind industrial symbiosis extend into all three dimensions of sustainability, also known as the triple bottom line, covering profit, planet and people (Kleindorfer et al. 2005, Tang and Zhou 2012). In its Action Plan for Circular Economy from 2015, the European Commission targets a more sustainable and resource efficient economy in Europe and identifies the need to promote industrial symbiosis and announces revised European regulation of waste in order to “to clarify rules on by-products to facilitate industrial symbiosis and help create a level-playing field across the EU” (EC 2015).

From an operations and supply chain management perspective, industrial symbiosis introduces new supplier-buyer relationships and forms a collaborative supply chain network between previously unrelated companies (Bansal and McKnight 2009, Miemczyk et al. 2012). The development of industrial symbiosis therefore requires some degree of shared strategic visions and collective decision-making, necessitating mutual recognition, trust and information sharing, and often some sort of central organization (Lowe 1997, Baas and Boons 2004, Chertow 2007). Also, newly introduced inter-dependencies often imply technical challenges relating to the quantity and quality of indus-

trial waste flows (Bansal and McKnight 2009). Furthermore, the success of industrial symbiosis networks can be undermined by the lack of economic incentives and by technological developments that change the balance in the industrial ecosystem (Mirata 2004).

Even though examples of industrial symbiosis networks are plentiful, and seem to contain numerous operations and supply chain management challenges, the industrial symbiosis phenomenon has not received much attention in the operations and supply chain management literature, even though Kleindorfer et al. (2005) recognized the importance of building bridges between sustainable operations management and industrial ecology. This paper postulates that an improved understanding of the supply chain collaboration challenges in industrial symbiosis networks will (i) be highly beneficial in understanding the sustainability performance of industrial symbiosis networks, (ii) provide directions to increase the feasibility and resource efficiency of industrial symbiosis networks, and (iii) provide research directions for supply chain management researchers interested in socially and environmentally responsible operations.

To achieve this goal, this paper contributes to the literature in several ways. First, the paper develops a theoretical framework that links industrial symbiosis to sustainable operations management and supply network collaboration. Secondly, the paper analyzes the industrial symbiosis phenomenon as a practice of sustainable operations management, discussing its stakeholders, drivers, and performance. Here, selected industrial symbiosis cases are used to demonstrate the arguments. Finally, the paper identifies organizational and operational challenges with respect to supply chain collaboration.

2.2 Related literature and theoretical framework

There are several streams of literature related to the discussion in this paper. First of all, the industrial ecology literature in which the concept of industrial symbiosis originated. Major relevant contributions will be cited throughout this paper. In addition, as industrial symbiosis represents collaborative efforts to increase sustainability, two streams of research within operations and supply chain management are relevant: sustainable operations management and supply network collaboration. In the following, a theoretical framework is developed based on these two streams.

2.2.1 Sustainable operations management

Following Kleindorfer et al. (2005), sustainable operations management can be understood as a collection of practices that integrate a company's profit and efficiency related objectives with broader (social) considerations of internal and external stakeholders and the impact on the natural environment. This does not necessarily cover sustainability in the literal sense of the word, only the fact that the management of production operations also considers environmental and social concerns. Ideally, this eventually leads to increased overall sustainability of the production operations.

Many stakeholders play a role in sustainable operations management, some more focused on environmental performance, others more focused on social performance (Meixell and Luoma 2016). On the one hand, organizational stakeholders include the supply network itself: upstream and downstream business partners, consumers, and employees (Linton et al. 2007). On the other hand, stakeholders that are external to the supply chain include governmental stakeholders, such as governments and trade associations, as well as community stakeholders, such as environmental organizations and people that live in geographical proximity of the industrial symbiosis network (Henriques and Sadorsky 1999). In general, these different stakeholders lead to pressure and incentives towards sustainability (Seuring and Müller 2008). This paper builds on the generally accepted view on sustainability according to which incentives and drivers behind sustainability boil down to profit-, planet-, and people-related issues and performance expectations (i.e. the triple bottom line) that influence a company's operations strategy (e.g. Kleindorfer et al. 2005, Linton et al. 2007, Carter and Rogers 2008, Diabat and Govindan 2011, Tang and Zhou 2012)

2.2.2 Supply network collaboration

Companies form a collaborative network to emphasize cooperation by for example working towards mutual goals, developing processes or products jointly, sharing the cost of investments, mitigating risk, sharing information (Kumar and van Dissel 1996, de Leeuw and Fransoo 2009).

In terms of collaborative effort, this paper distinguishes between organizational and operational aspects that relate to the development and organization of relationships and to the functioning of material exchanges, respectively. In addition, this paper distinguishes between supply chain integration and coordination as collaborative practices. In general, integration relates to strategic developments and to the flow of goods including informational and delivery

	Integration	Coordination
Organizational aspects	<ul style="list-style-type: none"> • Collaborative project definition • Knowledge transfer and integration 	<ul style="list-style-type: none"> • Incentive alignment • Collective learning
Operational aspects	<ul style="list-style-type: none"> • Product and delivery system • Information system 	<ul style="list-style-type: none"> • Supply demand agreements • Logistical synchronization

Figure 2.1: Overview of organizational and operational aspects of coordination and integration in collaborative supply networks.

aspects (Frohlich and Westbrook 2001, Vachon and Klassen 2007), whereas coordination relates to the management of the resulting dependencies between different supply chain entities emphasizing their joint decision-making and actions towards mutually defined objectives (Arshinder and Deshmukh 2008). In short, integration builds links between companies, whereas coordination aims to enable partners to work together effectively and efficiently. Figure 2.1 summarizes the main concepts identified with regards to supply network collaboration.

From an organizational perspective, strategic integration defines inter-dependencies in a supply network. Integration usually entails a communication setting to transfer and integrate knowledge and expertise, and often results in particular collaborative projects such as infrastructural development, product design, or process design (Vachon and Klassen 2007). In a collaborative supply network, knowledge and experience sharing contributes to the development of a mutual understanding of circumstances that affect companies, and help to develop core capabilities to address common challenges. The coordination of this “collective learning” entails analyzing circumstances and synthesizing improvements, and also engaging key stakeholders in collaboration (Simatupang et al. 2002). Furthermore, to make collaboration sustainable, companies have to coordinate the distribution of risks and benefits (Kumar and van Dissel 1996). In order to align incentives, companies in collaboration share objectives, make joint decisions, and often rely on each other’s trustworthiness (Hoyt and Huq 2000, de Leeuw and Fransoo 2009).

From an operational perspective, integration defines a production and delivery system. Consequently, logistical integration is characterized by exchang-

ing explicit information between companies, such as production plans and inventory levels, and implies better visibility of each other's tactical plans (Frohlich and Westbrook 2001, Vachon and Klassen 2007). Typically, logistical integration requires an information system that collects, stores, and works with operational data. The coordination of logistics (i.e. logistical synchronization) entails a mediation function that aims to match products with customer demand while lowering costs and minimizing uncertainties (Simatupang et al. 2002). Furthermore, to coordinate the terms of production and delivery, suppliers and customers typically make contracts and agreements (Jagdev and Thoben 2001).

Although collaboration emphasizes joint efforts and collective benefits, companies do not always share these equally, potentially leading to conflicts. Moreover, companies don't necessarily depend on each other to the same extent, leading to asymmetries in the relationship. As a result of low benefits and/or high risks, companies may not participate or exit the supply network. The increasing importance of sustainable supply chains makes it increasingly challenging to ignore collaboration across industries (Spekman and Davis 2016).

2.2.3 Theoretical framework

Figure 2.3 gives an overview of the main concepts from the previous sections, and thereby presents the theoretical framework this paper will use to analyze the industrial symbiosis phenomenon from an operations and supply chain management perspective. The framework considers stakeholders as well as collaborative supply network practices with the goal of improving sustainability performance within a geographical region. In the following, the paper first discusses the different stakeholders, and how their drivers, expectations, and management practices target the triple bottom line of sustainability. Subsequently, the paper focuses on the collaborative efforts in industrial symbiosis and analyzes operational and organizational aspects based on integration and coordination.

2.3 Industrial symbiosis – stakeholders, drivers, and performance

In the literature, industrial symbiosis is also referred to as industrial recycling networks, regional synergies, and eco-industrial parks (Lowe 1997, Schwarz and Steininger 1997, Chertow 2007, Geng and Côté 2002, Massard et al. 2012).

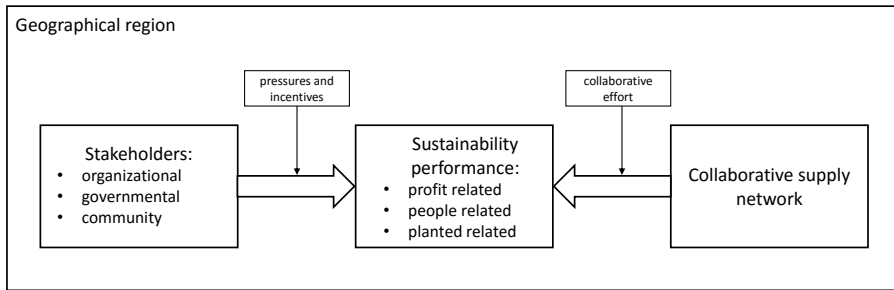


Figure 2.2: Theoretical framework to analyze the sustainability of industrial symbiosis networks.

Over the years, many such initiatives have been started, of which the Kalundborg industrial symbiosis network in Denmark is probably the world's best-known example (Chertow 2000, Jacobsen 2006). It is often also considered the archetypical industrial symbiosis network and is the textbook example used as inspiration for other industrial symbiosis initiatives.

2.3.1 Empirical data on industrial symbiosis practices

In order to provide an empirical basis to derive the general characteristics of industrial symbiosis, this paper expands the perspective beyond the Kalundborg example and relies on a collection of fifteen industrial symbiosis networks from around the world identified in the literature (see Table 2.1). The descriptions of the networks stem mainly from the literature on industrial ecology and environmental engineering. The purpose of this survey is not to present a comprehensive list of industrial symbiosis networks. For such a list, the reader is referred to Massard et al. (2012). Their overview does however not provide sufficient details for this research; therefore, this paper only uses selected networks that have detailed case descriptions in the scientific literature. The literature survey has been supplemented by a series of more in-depth interviews with stakeholders of the Kalundborg industrial symbiosis network including some of the participating companies and the organizational unit.

Table 2.1: List of industrial symbiosis networks

Industrial symbiosis	No. of companies	Exchange types ^a	Development types ^b	Organizational unit	Main reference in literature
Chamusca, Portugal (Relvao Eco Ind. Park)	15	B	D	Chamusca Municipality	(Costa and Ferrão 2010)
Eno, Finland (Uimaharju Industrial Park)	6	B; U	S	no	(Saikku 2006)
Guayama, Puerto Rico, USA	3	U	S	Wastewater Advisory Council	(Chertow and Lombardi 2005)
Humber region, United Kingdom	9	B; S	D	National Industrial Symbiosis Programme	(Mirata 2004)
Kalundborg, Denmark	11	B; U; S	S	Environmental Club; Symbiosis Institute	(Jacobsen 2006)
Kansas City, Missouri, USA	6	B	D	yes (name n.a.)	(Cimren et al. 2011)
Kwinana, Western Australia	15	B; U	D	Kwinana Industries Council	(van Beers et al. 2007)

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Industrial symbiosis	No. of companies	Exchange types ^a	Development types ^b	Organizational unit	Main reference in literature
Nanjangud, South India	14	B; S	S	no	(Bain et al. 2010)
Norrköping, Sweden (Handelo bioenergy complex)	4	B; U	D	yes (name n.a.)	(Martin and Eklund 2011)
Nova Scotia, Canada (Burnside Ind. Park)	n/a	B; S	S	no	(Geng and Côté 2002)
Rotterdam, The Netherlands	n/a	B; U	D	Deltalinqs	(Baas 2011)
Schkopau, Germany (Valuepark Schkopau)	14	B; S	D	no	(Liwarska-Bizukojc et al. 2009)
Styria, Austria	37	B	S	Karl-Franzens-Uni. Graz Partnership	(Schwarz and Steininger 1997)
Tianjin, China	35	B	D	TEDA Administrative Commission	(Shi et al. 2010)
Ulsan, South Korea	36	B; U	D	Korea Industrial Complex Corporation	(Behera et al. 2012)

^a Exchange types: B – by-products, U – utilities, S – services; ^b Development types: S – Spontaneous, D – Designed

2.3.2 Geographical characteristics

Industrial symbiosis can manifest over different geographical distances from co-localization in industrial parks to more regional developments (Chertow 2000). Industrial parks, for example in Kwinana and Ulsan, can turn into eco-industrial parks implementing industrial symbiosis between the already co-located industries (van Beers et al. 2007, Behera et al. 2012). Similarly, industrial symbiosis was developed inside the city of Kansas by engaging local production companies (Cimren et al. 2011). In Germany, several industrial areas in the Rhine-Neckar region are connected through waste exchanges leading to a more dispersed regional industrial symbiosis (Sterr and Ott 2004).

In some cases, there has been a significant top-down effort in designing or creating industrial symbioses by transforming existing industrial parks as well as implementing industrial symbiosis relationship within geographical regions. For example, the National Eco-Industrial Park Development Program in Korea, and the National Industrial Symbiosis Programme (NISP) in the United Kingdom are examples of such initiatives (Mirata 2004, Park et al. 2015). In other cases, industrial symbiosis has developed spontaneously as a bottom-up activity among companies. In Kalundborg, companies have been co-locating their production plants over the last forty years. The industrial symbiosis network in Eno, Finland, has an even longer history of engaging companies from the forestry industry in waste exchange for almost sixty years (Saikku 2006). According to Boons and Janssen (2004), the use of symbiotic relationships was more common in the nineteenth century when supply chains were more local. The globalization of supply chains reduced such interactions within local communities. As such, an increased focus on sustainability might again cause more localization.

2.3.3 Stakeholders

In accordance with the ecosystem analogy, industrial symbiosis is not just one supply chain, but a web of inter-dependencies between several companies, which are also part of their own supply chains, often also global supply chains. Besides the participating companies in the industrial symbiosis network, several additional stakeholders may be involved or affected. Since industrial symbiosis is often organized in industrial areas, they involve local employment and create job opportunities for the regional economy. In addition, industrial symbiosis affects the local community by their focus on waste reduction and energy efficiency. In the case of Kalundborg, the surrounding municipality is for instance an important stakeholder of the industrial sym-

biosis as it receives part of its residential heating from the network.

Regulatory bodies are important stakeholders for industrial symbiosis. On the (inter)national level, landfill and energy usage taxes and waste management regulations affect companies in industrial symbiosis. In fact, the EU Directive on Waste (2008/98/EC) mandates member countries to address waste and by-product reuse (Costa and Ferrão 2010). Similarly, regulatory pressure has been a driver behind industrial symbiosis initiatives in the United States, Australia, and Asia (Chertow and Lombardi 2005, van Beers et al. 2007, Behera et al. 2012). Governmental frameworks, such as the NISP in the UK, also facilitate information exchange among different industrial symbioses and provide a feedback loop for policy makers (Mirata 2004). Furthermore, regional governments often promote industrial symbiosis initiatives and attract regional investments, as well as provide financial support for their development (Behera et al. 2012). On the other hand, restrictive waste treatment laws can act as barriers to industrial symbiosis exchanges (Mirata 2004, Schwarz and Steininger 1997). An example is Kalundborg, where legislation restricts the feeding of local pigs with biomass produced as waste from an enzyme factory. As mentioned previously, the European Commission has a focus on adapting regulation to facilitate the exchange of by-products as part of its Action Plan for Circular Economy (EC 2015).

The role of non-governmental organizations is also important in many industrial symbiosis networks. As can be seen in Table I, more than half of the networks have an organizational unit, in the form of private organizations, public agencies, NGOs, as well as research institutes. Activities of the organizational unit in Ulsan, for example, are to find potential partners, conduct feasibility studies and to financially support and monitor the commercialization (Behera et al. 2012). In this case, and in many other industrial symbiosis cases, like in the NISP and Tianjin, the organizational unit is responsible for establishing collaboration in the industrial area to improve economic and environmental performance (Mirata 2004, Shi et al. 2010). In Kalundborg and in Kwinana, the organizational units comprise local industries that besides integrating environmental considerations into their profit-related objectives also integrate local community interests (Jacobsen 2006, van Beers et al. 2007). Additional activities of the organizational units include monitoring operations, facilitating studies of the industrial symbiosis, and disseminating knowledge (nationally and internationally) among other industrial symbiosis initiatives and academic researchers. Academic research institutes can also be involved in the organizational unit. For example, in Ulsan the person in charge (project champion) to drive industrial symbiosis development, to bring businesses to-

gether and stimulate their further participation was an academic researcher (Behera et al. 2012). In other another cases researchers are involved indirectly. For example, researchers from two universities conducted feasibility studies in the industrial symbiosis development in Rotterdam (Baas 2011). Also, researchers introduced the concept of industrial symbiosis to a local government in Portugal, when the local government was trying to establish a recycling network in the region of Chamusca (Costa and Ferrão 2010).

2.3.4 Expectations, drivers and sustainability performance

This section analyzes pressures and incentives of stakeholders according to which industrial symbiosis aims to deliver a collaborative sustainable supply chain effort. As depicted in Figure 2.3, these two aspects meet at the triple bottom line of sustainability; consequently, this section is structured around each of the three bottom lines: profit, planet, and people.

Profit related

Ideally, reusing by-products and scrap materials manifests a closed-loop system (French and LaForge 2006). Generally speaking, companies invest in closed-loop supply networks to gain economic benefits and to improve their environmental profile (Guide and van Wassenhove 2006). By-products in industrial symbiosis substitute raw materials and are often cheaper than the original raw materials due their negligible “production” costs and close proximity.

For example, in Nanjangud, Southern India, a company built its business on making oil from food-grade and biomass residues (such as coffee grounds, coconut, and sawdust) and selling it to a soap manufacturer (Bain et al. 2010). In Rotterdam, CO₂ recovery from heat suppliers made it possible to supply hundreds of greenhouses (Baas 2011). This created a new market for wasted emissions by substituting natural gas combustion at the greenhouses. Flue gas treatment in power generation from coal results in by-products like fly ashes and gypsum that can be reused in cement factories and by plasterboard manufacturers, allowing producers in the vicinity of the plants to save significant transportation costs by avoiding delivery from abroad (Schwarz and Steininger 1997, Jacobsen 2006). Additionally, power plants generate excess energy in the form of steam and heat, which can be reused in other industrial processes; consequently, their onsite production can be avoided (Chertow and Lombardi 2005). In Kalundborg, treated organic sludge from a large biotech company partnering in the industrial symbiosis is used as fertilizer, which

provides collective benefits. In fact, companies avoid disposal costs by supplying their organic waste to local farms instead of disposing it in a landfill and farmers obtain cheap organic fertilizer. In some cases, collaborative benefits emerge through shared logistical services, including storing processing and transportation (Bain et al. 2010, Geng and Côté 2002, Mirata 2004).

Investing in industrial symbiosis is generally considered as an efficiency improvement project with a return of investment of one to three years, however, this period can be exceeded in some cases (Mirata 2004, Baas 2011). Financial conditions of by-product treatment, storage, and delivery, is one of the first reasons why companies would reject the idea of industrial symbiosis. Furthermore, changing economic conditions may inhibit the expansion of the network or even cause companies to change back to more conventional economic development (Gibbs and Deutz 2007). Due to the substantial initial costs of industrial symbiosis relationships, companies often rely on financial support from private investors and governmental bodies (e.g. Behera et al. 2012, Shi et al. 2010). Without such support or in case of long payback periods, companies will often be reluctant to participate. For example, an industrial symbiosis initiative in Sweden was phased out when the research and external subsidies ended in 2006 (Mirata and Emtairah 2005, Baas 2011).

Planet related

Essentially, activities in the supply chain have the potential to degrade the natural environment by depleting its resources and deteriorating the environmental quality with waste disposal and pollution emission (Gupta 1995). In fact, industrial symbiosis reduces the amount of waste that would otherwise be landfilled or released as emissions to air or water and at the same time it improves companies' resource efficiency by emphasizing material reuse, avoiding the environmental impacts accompanying the extraction or production of virgin resources. Furthermore, utilization of wastewater components and excess heat and steam exchanges in industrial symbiosis contribute to the optimized use of energy and water that is one of the main features of industrial ecosystems (Frosch and Gallopoulos 1989). The Kalundborg industrial symbiosis is one of the pioneers of such energy and water cascading (Jacobsen 2006). Saving energy also reduces pollution emission indirectly by reducing the need for example electricity from power plants.

The companies' typical main driver in industrial symbiosis besides earning profit is to cope with environmental regulations. For example, in Portugal, a new environmental law, which was calling for improved waste management, triggered the organization of the Chamusca industrial symbiosis (Costa and

Ferrão 2010). Similarly, in Puerto Rico, a US regulation specifying that energy providers must also produce output other than electricity initiated steam production at the power plant, which served as a basis for the Guayama industrial symbiosis (Chertow and Lombardi 2005). In Australia, the increased community and governmental pressure to protect the marine environment initiated the establishment of the Kwinana Industries Council, which became the organizational unit for the local industrial symbiosis (van Beers et al. 2007).

However, companies don't always need regulatory incentives to trigger industrial symbiosis. For example, environment-oriented behaviour of companies was observed in Nanjangud, South India, where the recycling of non-hazardous industrial by-products and other wastes has been implemented in the absence of regulatory framework (Bain et al. 2010). On the other hand, industrial symbiosis activities do not always meet the environmental performance expectations, particularly when the involved companies are focused only on their economic interests and the broader environmental implications are overlooked (Ashton 2011).

Innovation in terms of clean technologies born from symbiotic relationships is rare since companies often focus on the reuse of waste, and not its prevention. Consequently, an important concern about industrial symbiosis is that it perpetuates waste streams instead of preventing them (Duflou et al. 2012). For example, promoting the cogeneration heat and power plant in the Humber region industrial symbiosis could potentially counteract the feasibility of any future renewable energy projects (Mirata 2004). At the same time, national initiatives to ensure a CO₂ neutral energy system in Denmark limit the long-term viability of leveraging excess utilities from the central power plant in the Kalundborg industrial symbiosis.

Although industrial symbiosis is typically based on old production technologies, innovation in products and processes can certainly play a role. For example, in the Handelö industrial symbiosis, biofuel production has been researched and implemented on industrial scale, and it now successfully fuels public transportation vehicles in Norrköping (Martin and Eklund 2011). In Kalundborg, small scale production plants have recently been implemented in order to test and scale up algae farms producing biomass fed on wastewater and to produce second generation biofuel from wheat straw. Furthermore, the research and development related to by-product reuse contributed to environmentally superior technical and organizational innovations in the German chemical industry (Sterr and Ott 2004). Therefore, industrial symbiosis also has the potential to be a driver of innovation for regional sustainability (Baas 2011).

People related

The people affected by operations include employees, consumers, as well as the general population living in the proximity of the supply chain operations (Tang and Zhou 2012). In fact, industrial parks employ people on a large scale, and their contribution to the local community's development can therefore be significant. Accordingly, many industrial symbiosis initiatives were primarily driven by job creation opportunities (Gibbs and Deutz 2007). For example, the Kalundborg industrial symbiosis, which is a medium-sized symbiosis, provides jobs to more than four thousand employees, a considerable share of which would not be employed without the activities fostered by the industrial symbiosis; and the relatively small-scale development of the Valuepark Schkopau in Germany created seven hundred jobs (Liwerska-Bizukojc et al. 2009). A new production unit to utilize excess steam in Ulsan, South Korea, resulted in more than a hundred new jobs (Behera et al. 2012).

Companies in industrial symbiosis have also been known to promote the personal development and well-being of their employees. Also, the organizational unit of the Ulsan industrial symbiosis organizes training sessions to educate people and guide companies in the creation of a better work environment (Behera et al. 2012). Additionally, for active public promotion and encouraging public participation in Ulsan, successful industrial symbiosis cases are advertised through electronic media and newspaper.

By reducing the companies' environmental impact, industrial symbiosis also enhances the local community's image with cleaner landscapes, air and water. Industrial symbiosis may also incorporate waste streams (e.g. solid waste and wastewater) from the local municipality, and excess heat can also be supplied to the local community (Saikku 2006, Jacobsen 2006, Baas 2011). As a result of available jobs, a healthy environment, and economic potential, industrial symbiosis has the potential to attract people to municipalities, which might otherwise face decreasing population, thereby contributing to regional development.

Industrial symbiosis not only emphasizes social responsibility by employment, but also by maintaining close social relationships within the supply networks (Schwarz and Steininger 1997). Social networking is often used to create a balanced business environment and enhance collaboration (Lamming et al. 2000). Indeed, as previously mentioned, trust, open communication, and joint problem solving are essential for the functioning of the industrial symbiosis, and are leveraged through social networking (Baas 2011). Thereby, companies in industrial symbiosis emphasize transparency and disseminate information among business partners. According to Carter and Rogers (2008),

transparency also works the other way around, by actively engaging stakeholders to secure their commitment and improve supply chain processes. As transparency should also reduce unethical (or illegal) behaviour, social sustainability is further improved, while at the same time the transaction costs for external stakeholders interested in assessing a companies' social responsibility is reduced (Carter and Rogers 2008).

2.4 Supply network collaboration in industrial symbiosis

Figure 2.1 summarized the organizational and operational aspects of the collaborative efforts between companies in industrial symbiosis networks that facilitate sustainability performance. The following sections give an overview of challenges that the collaboration faces, discussing first the organizational inter-dependencies and the role of organization and secondly the operational aspects of industrial symbiosis developments.

2.4.1 Organizational challenges in industrial symbiosis

Industrial symbiosis networks can create a context for collective problem definition and an interface to develop solutions in a collaborative manner (Mirata and Emtairah 2005). An organizational unit can facilitate these processes. industrial symbiosis examples show the importance of centrally organized local meetings (e.g. business match-making) where companies have opportunity to meet each other, attract new companies and establish personal relationships (e.g. Costa and Ferrão 2010, Behera et al. 2012). On these meetings, regional problems, stakeholder expectations and development plans are discussed (e.g. Mirata 2004, Costa and Ferrão 2010, Baas 2011). The organizational unit also provides a shortcut between the companies and the local authorities and may be used to provide information about environmentally sustainable actions (Mirata 2004). Such communication channels allow the presentation of ideas, the exchange of project experiences, and learning about stakeholder expectations (Costa and Ferrão 2010). Knowledge and experience sharing emphasizes the collective learning of companies, which enhances their collective capacity to identify new perspectives for development (Simatupang et al. 2002). Collective learning in industrial symbiosis facilitates the understanding of region-specific capabilities and cultural change associated with sustainability (Gibbs and Deutz 2007). The resulting region-specific knowledge allows companies to identify common problems and jointly work

out mutually beneficial solutions. Identifying incentives can lead to collaborative projects for sustainability improvements where companies share interests. For example, in Kalundborg, groundwater deficit had been a collective problem for water-consuming industries for decades. As a result of collaboration a number of private and public projects has been initiated including symbiosis between water-consuming industries (Jacobsen 2006). Collective learning may also enhance the innovation capability of companies (Bansal and McKnight 2009); thus, collective learning in industrial symbiosis may increase the regional competitiveness in a sustainable way. For example, in Tianjin, to prevent further farmland degradation companies developed an innovative technology to produce new soil from a combination of sea sediment, caustic soda sludge and fly ash (Shi et al. 2010). Especially for SMEs, such external inputs are often a necessary (but not sufficient) condition for development of environmental capabilities (Lee and Klassen 2008).

Although a central organization may play an important role in industrial symbiosis, the supply network is also self-organized by the participating companies (Lowe 1997). Coordination of businesses in the industrial symbiosis network ensures long-term sustainability with strategic alignment. Incentive alignment between companies in an industrial symbiosis is facilitated by mutually shared interests for economic gains and reduced environmental impact. Their long-term commitment also depends on the equivalent sharing of risks and benefits (Behera et al. 2012). On the other hand, incentive alignment is difficult to achieve when companies are forced into contracts without knowing the potential risks and benefits of participating in industrial symbiosis. In the Humber region industrial symbiosis in the UK, for example, only around 20 out of 150 contacted companies showed interests in the program due to the lack of trust and information (Mirata 2004). Furthermore, inter-dependencies in industrial symbiosis are sometimes asymmetric, which means that one party has more power than the other(s). In fact, industrial symbiosis often settles around “powerful” companies, for example power plants, water supply/treatment facilities and chemical producers, which are able to provide a large amount of by-products, excess utilities, or services (Jacobsen 2006, Liwarska-Bizukojc et al. 2009). These so-called anchor organizations can create a critical mass for industrial symbiosis development, but their market exit is also a potential risk for the symbiosis (Chertow 2000).

Losing a by-product supplier or buyer, for example due to relocation, or due to a change in the by-product characteristics, can endanger the integrity of the symbiotic network. Furthermore, by-product exchanges can create a technological lock between the companies. Building a symbiotic exchange on

technologies that may become obsolete in the future undermines the sustainability of industrial symbiosis. Furthermore, industrial symbiosis is exposed to changes in the contemporary regulatory framework.

It is however important to note that not all wastes are hazardous, and that waste is unlikely to be entirely eliminated through cleaner production and pollution prevention (Erkman 1997, Lowe 1997). Therefore, industrial symbiosis can be a long-term, feasible option for companies that generate non-hazardous wastes if the waste streams are sustained. Nevertheless, if companies don't see or lose economic incentives in the by-product exchange, they will not participate or exit the industrial symbiosis. Consequently, the main organizational challenge concerning the sustainability of industrial symbiosis is to integrate sustainable technologies, which can run without undermining their own basis. A further challenge is to sustain the economic incentives between the participants as well as to win their trust in the collaboration. Governmental regulations and central organization on regional level can facilitate these initiatives. Indeed, trust and consistent information are important enablers of strategic alliance in collaborative supply networks (Hoyt and Huq 2000). In industrial symbiosis, trust among the broad set of stakeholders (e.g. industries, governments, environmental and local interests groups) is an enabler of knowledge and information sharing and is essential for long-term business relationships (Baas 2011). Trust between companies is determined by preexisting links but can also be developed through social networking.

2.4.2 Operational challenges in industrial symbiosis

Operational aspects of industrial symbiosis comprehend the management of material exchanges. Generally speaking, the spectrum of material exchanges in industrial symbiosis spans from simple dyadic (supplier-buyer) relationships to networks involving several buyers and suppliers. An industrial symbiosis typically involves multiple of such inter-dependencies. Additionally, companies in industrial symbiosis may complement incoming by-product streams with original raw materials. Dyadic relationships between two plants in industrial symbiosis may evolve to reciprocal by-product exchanges; for example, in Nanjangud, a beverage producer provides coffee grounds to an oil processor, who in turn provides biomass fuel to the beverage producer (and other companies).

In industrial symbiosis, a supplier can be a sole provider of industrial waste for several buyers (Bain et al. 2010). Cogeneration power and heat plants typically supply excess steam and heat to more than one buyer due to the fact that this form of excess energy is useful in many industries (Jacobsen

2006). Similarly, one can receive industrial wastes from more than one plant. For example, in Ulsan, a company receives and processes zinc waste from three plants inside the industrial symbiosis and provides the value added product to a paint producer (Behera et al. 2012). In fact, relationships within industrial symbiosis can connect more levels of actors leading to a chain of suppliers and buyers. Moreover, a company may participate in more material exchanges at the same time. For example, in Nova Scotia, industrial waste collectors recover by-products such as paints, oils and scrap materials (Geng and Côté 2002). Nevertheless, ongoing production is not always necessary to have a feedstock of by-products. For example, in Kwinana, a stockpile of gypsum waste from the 1980s is now utilized by plasterboard manufacturers and local farmers (van Beers et al. 2007).

By-products and scrap materials are frequent output of process industries, such as chemical, oil, steel, forestry, agricultural, and food industries Fransoo and Rutten (1994). Due to the divergent production processes, many products are produced from a few raw materials, and production often yields unwanted but also un-avoidable by-products. Based on the available case studies, it is clear that industrial symbiosis mainly involves process industries and often involves water and energy treatment and supply. Sometimes, industrial symbiosis also incorporates other waste streams like electronic waste, end-of-life vehicle handling or municipal solid waste treatment (e.g. Geng and Côté 2002, Costa and Ferrão 2010, Bain et al. 2010).

The feasibility of industrial symbiosis is affected by its geographical range (Sterr and Ott 2004, Gibbs and Deutz 2007). Intuitively, by increasing the geographical range, the number of potential partners is higher and total supply and demand of by-products (and excess utilities) also grows. Furthermore, by involving more companies in the by-product exchange, the economic viability improves and the system becomes more resistant to fluctuations or failures (Lowe 1997, Sterr and Ott 2004). However, increasing the distance inherently decreases the cost effectiveness of the by-product exchange and adds to the environmental impact due to the increased effort in transportation. Moreover, longer distance in case of perishable materials is explicitly infeasible. In short, there is a trade-off between the geographical range and the efficiency of an industrial symbiosis.

Operational considerations in industrial symbiosis relate to the management of production, transportation, and use of industrial waste, as well as the synchronization of these logistical activities between supplier and buyer on a tactical level. Before usage, exchanged materials often need to go through additional treatment processes, storage, and transportation (Duflou et al. 2012).

The treatment of by-products may require individual value adding processes such as mixing, separating, forming, or chemical reactions (Flapper et al. 2002). The resulting bulk materials can be transported by trucks. In some industrial symbioses, a joint distribution service is used to reduce the logistical effort (e.g. Geng and Côté 2002). Furthermore, utility exchanges (e.g. steam and water) usually involve pressure conservation and settling and require a pipeline network for delivery (Jacobsen 2006). On the other end of the supply chain, being able to use a by-product possibly involves process adjustments because it might differ from the previously used original raw materials (Duflou et al. 2012).

Natural variations in product quality lead to variability in by-product quantity (through different yields) and quality (Fransoo and Rutten 1994). Depending on the requirements of the buyer, such quality variations can inhibit symbiotic relationships (Bansal and McKnight 2009). Furthermore, the availability of industrial waste is the result of a push process, meaning that surplus or shortage can occur due to the variability in supply and demand, and the different seasonal characteristics in different industries. In order to deal with surplus and shortage in industrial symbiosis, industrial waste may need to be stored, excess waste might have to be disposed, additional original raw materials may need to be purchased, or limited waste quantities might have to be divided over multiple interested buyers. From the cases, it seems that a significant part of the exchanged by-products in industrial symbiosis are durable, meaning that inventories can be stored. Nevertheless, holding by-product inventory requires additional space and incurs costs. Other by-products like waste oils and biomass are perishable. Moreover, the exchange of utilities, such as steam and heat, implies very strict perishability.

Generally speaking, by-products are different from original materials, and consequently, operating with by-products increases the effort in designing and operating storage facilities and production systems. Also, alternating between by-products and original raw materials or combining them complicates the production. This includes both technical aspects such as storage space and equipment connectivity, as well as operational aspects such as inventory management, purchasing of raw materials, and planning of production with multiple material sources. Furthermore, the sourcing of by-products and original raw materials simultaneously might affect agreements with original raw material suppliers, potentially leading to higher costs.

Aggregate and temporal logistical information concerning waste streams is important in order to evaluate potential by-product exchanges. Therefore, a central information system, where companies are able to share information

	Integration	Coordination
Organizational aspects	<ul style="list-style-type: none"> • Create non-hazardous by-product synergies between environmentally sustainable processes • Establish an organizational unit that integrates local industrial communities and authorities by offering a communication platform 	<ul style="list-style-type: none"> • Sustain economic incentives for long-term cooperation by sharing costs, risks, and benefits of by-product synergies • Engage diverse stakeholders in social networking emphasizing local problems and solutions
Operational aspects	<ul style="list-style-type: none"> • Implement a local by-product collection and delivery system • Integrate by-product treatment, storage and reuse into operations • Share aggregated and temporal information on by-product flows 	<ul style="list-style-type: none"> • Combine original and by-product materials in procurement and production planning • Manage seasonal variability and quality and quantity uncertainties in by-product flows; match by-product supply and demand

Figure 2.3: Identification of organizational and operational challenges in industrial symbiosis networks

about their waste streams and learn about other companies, can be used in the development phase of industrial symbiosis (Sterr and Ott 2004, Grant et al. 2010). It can however be challenging to obtain such information from companies. The assessment of material flows (e.g. quantity, quality, distribution over time) can be used to optimize the network design and material flows in terms of costs and environmental impacts. For example, the implementation of the Kansas City industrial symbiosis was supported by an optimization model that evaluated the different configurations of potential participants (Cimren et al. 2011). However, temporal dynamics of supply and demand of by-products have so far not been captured by information systems or by production and inventory management (Grant et al. 2010, Cimren et al. 2011). Nevertheless, a resulting logistical synchronization capability would have positive impact on the supply network's operational efficiency.

Figure 3 summarizes the organizational and operational challenges of industrial symbiosis that were identified in the analysis.

2.5 Conclusion and future work

To improve the environmental sustainability of operations management, recent research suggested building bridges between operations management and industrial ecology. Industrial symbiosis, as a concrete implementation of industrial ecology, pursues industrial ecosystem thinking in which companies from different industries form a supply network collaboration based on

the local recycling of industrial waste, by-products, and excess utilities.

Previous literature finds that industrial symbiosis networks support regional sustainable development by improving the companies' resource efficiency and competitiveness, creating new employment, and by contributing to a cleaner natural environment. Companies in industrial symbiosis networks show significant effort in achieving competitive advantage in a collectively beneficial way by emphasizing cooperation.

From a supply network collaboration perspective, this paper shows that industrial symbiosis emphasizes transparency, shared cultural norms, social networking, and trust, which all allow companies to understand each other's capabilities and to form strategic alliances based on economic drivers as well as social and environmental responsibility. The existence of central organizational units distinguishes industrial symbiosis from other supply network collaborations. The organizational unit contributes to the development of industrial symbiosis networks by functioning as a central hub that augments communication between stakeholders, facilitates business match-making and helps region specific collective learning. As such, it seems to help address some of the organizational challenges identified in this paper.

Industrial symbiosis also implies risks for the participants due to high levels of inter-dependency in supplier-buyer relationships; consequently, companies have concerns regarding such long-term collaboration. Nevertheless, in many of the analyzed cases, industrial symbiosis demonstrated resilience over several decades. Moreover, examples show that companies in industrial symbiosis networks, driven by profitability and resource scarcity as well as pressure of governmental regulations, are able to deliver innovative solutions in terms of non-hazardous waste utilization. Yet, focusing and integrating sustainable technologies based on waste exchange and engaging companies in long-term partnerships are great challenges to industrial symbiosis.

On an operational level, industrial symbiosis engages companies in the collection, treatment and storage of by-products and delivering them to other producers. Previous research, which often modeled by-product exchanges on an aggregate level, points to trade-offs between the geographical distance between supplier and buyer and the related resource efficiency of industrial symbiosis. However, temporal dynamics in industrial symbiosis have not been addressed. One key question is how to manage a lack of synchronicity between by-product supply and demand, which originates at different production facilities with potentially different seasonal characteristics as well as short-term variability. This implies inventory management challenges, which could possibly be addressed by synchronizing by-product exchanges between

multiple suppliers and buyers. This would reduce by-product quantity uncertainties and potentially increase the feasibility of long-term supply and demand agreements. Furthermore, dealing with quality variations of by-products and their integration with other raw material sources can lead to procurement and production management challenges. These problems might be addressed with further by-product treatment (e.g. separation and mixing) and by alternating between or combining by-products and original raw materials. Consequently, there are ample opportunities for further research regarding by-product inventory management and production planning that combine different by-products with original materials.

Even though financial considerations remain the driving factor of companies within industrial symbiosis, increasingly scarce natural resources and increasing regulation on waste and emissions will cause companies to more and more consider the environmental and social implications of their operations. In the EU, the European Commission's Action Plan for Circular Economy identifies industrial symbiosis as a central strategy to increase resource efficiency in order to promote European environmental sustainability and reduce the dependency of European industries on external raw material supplies. Clearly, in order to be successful, industrial symbiosis needs specific circumstances, which involve facilitating regulatory frameworks, and require long-term commitment from companies. However, in light of new economic, environmental, and social challenges, the local industrial waste recycling leveraged in industrial symbiosis networks might be a viable route towards the sustainability of production operations if the underlying technologies are selected carefully, and the European action plan suggests a number of initiatives to improve the conditions for industrial symbiosis.

The overview of the key organizational and operational challenges given in this paper with regard to supply chain collaboration supports a much needed improved understanding of the collaborative supply network dimension of industrial symbiosis networks, helping to assess the economic, environmental, and social performance of current and future initiatives.

CHAPTER 3

Resource-based competitive advantage

This chapter is based on a manuscript to be submitted for publication under the title “Toward a theory of competitiveness in industrial symbiosis networks: A resource-based view”. The manuscript is co-authored by Gábor Herczeg, Renzo Akkerman and Michael Zwicky Hauschild.

Abstract

Industrial symbiosis is built on synergistic transactions between firms to mimicking the flow of materials in natural ecosystems: undesired production output becomes raw material in another industrial process. From a management perspective, industrial symbiosis is a proactive environmental strategy emphasizing community, connectedness and cooperation in a system of diverse organizations including firms and external stakeholders. However, economic considerations remain pivotal for participating firms. Consequently, firms collaborate in industrial symbiosis for collective competitive advantage. This paper grounds industrial symbiosis in the theory of competitiveness using eight previously published cases. Based on the natural-resource-based view of the firm, the relational view of cooperation, and the contingent resource-based view the key capabilities and resources in industrial symbiosis networks are attributed to three dimensions: the proactive environmental stance of individual firms, the cooperative relations, including strategic alliance and network embeddedness, and the business environment, involving institutionalization and an organizational unit that are contingent to the network. It is argued that industrial symbiosis networks are difficult to imitate because their initiation draws on tacit personnel skills, faces partner scarcity, and involves institutionalization; furthermore, their progression requires life cycle thinking, inter-organizational asset interconnectedness, and an organizational unit that coordinates the sustainability effort and the transactions in the network.

3.1 Introduction

Industrial operations have long-lasting effects on our environment, including the communities we live in. This is mainly caused by an ever increasing extraction and processing of raw materials and the production of undesired outputs in the form of waste and emissions to the environment. Firms that address sustainability concerns, such as resource depletion and pollution, often pursue environmental strategies that are to improve internal operations and extended supply chains (Kleindorfer et al. 2005). However, competitiveness remains pivotal in the development of these strategies (Corbett and Klassen 2006, Vachon and Klassen 2008).

Sustainable supply chain management indicates opportunities related to the use of undesired production outputs, such as waste and by-products (Linton et al. 2007). Consequently, pollution prevention contributes to increased resource productivity, innovation, and competitiveness (Porter and van der Linde 1995). Furthermore, an industrial ecosystem suggests an ideal, integrated production model where the consumption of energy and materials are optimized, waste disposal is minimized, and the undesired outputs of one process serve as raw material another process (Frosch and Gallopoulos 1989).

A well-known manifestation of industrial ecosystems is industrial symbiosis. It is defined as a collective approach to competitive advantage based upon substituting virgin raw materials of a firm with another firm's wastes or by-products (Chertow 2000). Industrial symbiosis initiatives are numerous and can be found all over the world, from the well-known 50-year-old example in Kalundborg, Denmark (Jacobsen 2006) to more recent examples in Canada (Bansal and McKnight 2009), the United States (Cimren et al. 2011) and Asia (Zhu and Côté 2004).

Industrial symbiosis involves a tight network of diverse supply chain relationships, where firms capitalize on the opportunities afforded by geographical proximity, excess materials, and potentially useful wastes (Bansal and McKnight 2009). Furthermore, opportunities to obtain competitive advantage through industrial symbiosis are often attributed to improved resource productivity, innovative product or process changes, increasing revenue, diversifying business, and managing risk (Esty and Porter 1998, Lombardi and Laybourn 2012). Even though it is argued that industrial symbiosis contributes to collective competitive advantage, it has not been previously grounded in the theory of competitiveness (Hoffman et al. 2014).

In this paper we therefore address industrial symbiosis using the resource-based theory of competitiveness. More specifically, we investigate the initiation and progression of industrial symbiosis networks, based on the natural-

resource-based view of the firm (Hart 1995), the relational view of cooperation (Dyer and Singh 1998), and the contingent resource-based view (Aragón-Correa and Sharma 2003). We identify the key resources and capabilities and analyze their role in industrial symbiosis, using a survey of 8 previously published case studies. By induction, we derive propositions on how supply chain management leverages these resources and capabilities on the level of the firm, the network, and the business environment, to obtain a competitive advantage during the initiation and progression of industrial symbiosis.

The remainder of this paper is organized as follows. In the next section, we describe our methodology including the theoretical foundation and data sources we draw on. Afterwards, we elaborate on three fundamental dimensions of resources and capabilities in the management of industrial symbiosis, and then discuss them to derive propositions that build toward a theory of competitiveness in industrial symbiosis networks. Finally, we conclude our findings, provide managerial implications, and outline future research opportunities.

3.2 Methodology

Industrial symbiosis has been extensively studied for almost two decades (Yu et al. 2013). There is a vast amount of empirical research narrating industrial symbiosis examples from all over the world, explaining the role of integration (Zhu and Côté 2004), quantifying its economic and environmental impacts (Jacobsen 2006), identifying triggers and barriers of development (van Beers et al. 2007), emphasizing the importance of coordination and cooperation (Bansal and McKnight 2009), and reporting on the role of facilitator organizations (Paquin and Howard-Grenville 2012).

In this paper, we use existing case studies of industrial symbiosis for building theory. Theory building from cases is an inductive form of research producing testable theoretical propositions from data (Eisenhardt and Graebner 2007). Using existing cases has been deemed appropriate in situations where empirical evidence is largely contained in case studies (Yin and Heald 1975, Jauch et al. 1980).

To build theory based on multiple cases researched from different aspects it is necessary to first define a common ground for analysis (Eisenhardt and Graebner 2007). Our objective is to theorize competitive advantage in industrial symbiosis including the level of the firm, the network, and the business environment. We choose the resource-based view to ground our work, because this theory attributes sustained competitive advantage to idiosyncratic

resources of the firm (Barney 1991). The natural-resource based view focuses on capabilities and resources developed driven by challenges and constraints posed by the natural environment (Hart 1995), which are also key drivers for industrial symbiosis. In addition, the theory has been extended to cooperative relationships (Dyer and Singh 1998) between firms, thereby capturing cooperation and coordination in industrial symbiosis networks. Furthermore, the contingent resource based-view of environmental strategies (Aragón-Correa and Sharma 2003) points to contingencies of the general business environment that moderate the impact of resources and capabilities on competitive advantage, which is a relevant extension in case of industrial symbiosis. Before introducing data, we elaborate on the logic behind the resource-based view and on its terminology.

3.2.1 Resource-based theory of competitiveness

In general, resources are defined as tangible and intangible firm-specific assets that could be thought as a strength (or weakness) of a given firm (Wernerfelt 1984). Example for resources are: a good location for a business, products and distribution channels, contracts, patents, production procedures, skilled employees, managerial routines, tacit know-how, and access to information.

Resources are a source of competitive advantage if they are valuable in the sense that they help to exploit opportunities and/or neutralize threats, and if they are rare among competitors (Barney 1991). Furthermore, inter-organizational competitive advantage is obtained from inter-firm relation-specific resources developed in strategic alliances (Dyer and Singh 1998).

By definition, a resource possessed by a large number of other firms, or a resource that is perfectly imitable or substitutable cannot be a source of sustained competitive advantage (Barney 1991). For example, assets that are available on commercial markets typically cannot be associated with sustained competitive advantage. In general, resources can be imperfectly imitable for one or a combination of three reasons: resources are developed under unique historical conditions, resources are socially complex that is they are a result of diverse personal interactions, or the link between competitive advantage and resources is causally ambiguous (Dierickx and Cool 1989). Furthermore, inter-organizational competitive advantage is imperfectly imitable as a result of asset interconnectedness, partner scarcity, resource indivisibility and institutions (Dyer and Singh 1998).

The natural-resource-based view of the firm attributes competitive advantage to dynamic capabilities and resources associated with a proactive environmental strategy (Hart 1995, Hart and Dowell 2011). Dynamic organiza-

tional capabilities are the ability to integrate, build, and reconfigure internal and external competences (resources) to achieve new and innovative forms of competitive advantage (Teece et al. 1997). The combination of internal and external resources implies competitive action complemented with cooperative action and the integration of stakeholder perspectives (Hart 1995). A proactive environmental strategy, such as pollution prevention or product stewardship, is a dynamic strategic capability associated with specific assets, patterns of behavior and learning, and development paths of managerial routines (Teece et al. 1997, Hart and Dowell 2011).

A proactive environmental strategy enables an organization to align itself with changes in the business environment (Aragón-Correa and Sharma 2003). The business environment implies contingencies, such as uncertainty, complexity, and munificence, moderating the likelihood that a firm will use its capabilities and resources to develop environmental strategies and the association between an environmental strategy and competitive advantage (Aragón-Correa and Sharma 2003).

3.2.2 Selected cases studies of industrial symbiosis

A multiple-case research method, has to undergo a clear case selection procedure (Larsson 1991), in which the selection of cases needs to cover the spectrum of variables that differentiate over the population (Eisenhardt 1989). Even though published case studies of industrial symbiosis are generally not analyzed from a resource-based view, case descriptions do often include a significant amount of material on organizational resources and capabilities.

There are many theoretical aspects of industrial symbiosis to consider, including its different spatial configurations, its evolutionary stages, and its type of organization (Chertow and Ehrenfeld 2012). In our case selection, we draw on the organizational aspect of industrial symbiosis networks because organizational capabilities and resources are central for our paper. The polar types of our spectrum of industrial symbiosis are spontaneous (self-organized) and facilitated (centrally planned) organization (Chertow and Ehrenfeld 2012). While self-organized industrial symbiosis evolves spontaneously, driven in part by regulatory demands; facilitated symbioses are typically governmental initiatives (Lowe 1997). However, a common feature of both types is that they typically manifest a central organizational unit that institutionalizes industrial symbiosis among the firms and external stakeholders (Chertow and Ehrenfeld 2012).

A prime example of spontaneous emergence is the industrial symbiosis in Kalundborg, Denmark, where symbiotic activities date back to the early

1970's, initiated by the utilization of by-product flows from a thermal power plant and an adjacent oil refinery. Since then, organizational units have evolved establishing a culture of cooperation across industries and regional development efforts (Jacobsen and Anderberg 2004). Another example is the Guitang Group in China, which has been integrating sugar refining with industrial processes outside their core business for decades; consequently, they operate several by-product flows across their value chains (Zhu and Côté 2004).

Governmental initiatives, such as the National Eco-industrial Park Development Program in South Korea and China, are driven by a desire to update aging industrial park infrastructure, reduce costs through increased cooperation, and identify new business opportunities based on available production outputs while reducing environmental impact (Behera et al. 2012, Yu et al. 2014). The National Industrial Symbiosis Programme (NISP) in the UK is an umbrella program for developing industrial symbiosis networks in different regions of the country through regional development agencies (Mirata 2004).

In our collection of empirical data on industrial symbiosis, we only rely on publications built on structured interviews with managers and quantitative data to build theory around industrial symbiosis. Furthermore, we have only selected cases for which the research material offered sufficient description for the later inference. As a result, we selected eight different well-studied cases of industrial symbiosis networks resembling the list that was used by (Chertow and Ehrenfeld 2012). The cases are summarized in Table 3.1.

3.3 Identification and analysis of capabilities and resources

In general, firms in industrial symbiosis bring an environmentally proactive strategy in action. They focus on the productive use of undesired production outputs instead of their ultimate prevention (see Table 3.1 for a list of by-products and wastes used in the selected cases). Although industrial symbiosis networks are partly reactions to environmental regulations, they are proactive because they exhibit a consistent pattern of environmental practices including voluntary actions over time (Sharma and Vredenburg 1998).

Furthermore, industrial symbiosis networks emphasize community, cooperation, and coordination among firms, which serves to protect environmental integrity, social equity, and economic prosperity of the region (Bansal and McKnight 2009). In other words, firms in industrial symbiosis networks build strategic alliances.

Table 3.1: Overview of the selected industrial symbiosis networks

Industrial symbiosis	Typical facilities involved	By-product production lines	Organization	Organizational Unit /Institutionalization	Reason for initiation	References
Kalundborg, Denmark	Coal-fired power plant, pharmaceuticals, plaster board, oil refining, fish farming	Water, wastewater, sulfur, steam, sludge, fly ash, yeast and organic residuals	Spontaneous	Environmental Club; Symbiosis Institute	Emission regulations; economic motivation is connected to direct savings and indirect operational performance	Jacobsen and Anderberg (2004), Jacobsen (2006), Ehrenfeld and Gertler (1997)
Kwinana, Australia	Coal-fired power plant, chemicals, fertilizer producers, cement, construction, oil refining	Organic waste, sludge, acid, ash, dust, chemical catalysts, organic waste, energy production	Spontaneous	Kwinana Industrial Council; Center of Sustainable Resource Processing	Regulations regarding air and water quality; sustainable minerals processing is concerned with finding ways to eliminate waste	van Beers et al. (2007)
Barceloneta, Puerto Rico	Coal-fired power plant, chemical refining, pharmaceuticals	Wastewater, condensate, steam, ash, solvents	Spontaneous	Barceloneta Wastewater Treatment Corporation Advisory Council	Comply with water pollution regulations; motivated by lowering cost of waste disposal and accessing limited water supply	Ashton (2008, 2009, 2011)
Styria, Austria	Sawmills, mining, textiles, chemicals, power plant, cement plant	Ash, plastics, sludge, wood and paper, heat, petrol coke, slag, dust, oil	Spontaneous	Karl-Franzens-Universitat Graz Partnership	Triggered by the additional revenue and avoided disposal and procurement costs	Schwarz and Steininger (1997)

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Industrial symbiosis	Typical facilities involved	By-product production lines	Organization	Organizational Unit /Institutionalization	Reason for initiation	References
Guitang Group, China	Sugar refining, alcohol, pulp and paper mill, cement, alkali recovery, agriculture	Bagasse, molasses, sludge, alcohol residue, alkali, ashes, filter mud	Spontaneous	Private owners	Environmental regulations addressing waste and pollution in the sugar industry; additional revenues	Zhu and Côté (2004), Zhu et al. (2007)
Ulsan, South Korea	Oil, chemicals, incineration, metal processing, paper mill	Wastewater, biogas, steam, metal	Facilitated	Korean Industrial Complex Corporation	Meet environmental quality standards in the region	Park and Won (2007), Park et al. (2008), Behera et al. (2012), Park and Park (2014), Park et al. (2015)
Tianjin Economic Development Area, China	Pharmaceuticals, food and beverages, electronics, machinery	Water, metals, chemical substances, ash, slag, organic residues	Facilitated	Tianjin Economic Development Area Environmental Protection Bureau	Environmental regulations and cost savings	Shi et al. (2010), Yu et al. (2014)
Industrial Areas, United Kingdom	Coal-fired power plant, oil refining, plastic, rubber, plastic recycling, paper mill, chemicals, food and fish processing, metals, furniture	Steam, electricity, technology, waste carpets, fuels, edible oil, electronic waste	Facilitated	National Industrial Symbiosis Programme	Landfill tax and climate change levy	Mirata (2004), Paquin and Howard-Grenville (2012), Paquin et al. (2014)

The progression of industrial symbiosis networks entails structural and cultural embeddedness of a system of actors. In this system, social and business relations are combined, and network ties enable the development of shared norms that shape opportunities for collaboration, thus contributing to the growth of the network (Chertow and Ehrenfeld 2012).

Finally, the business environment in which industrial symbiosis manifests provides unique institutional conditions. Typically, an organizational unit is associated with the institution of industrial symbiosis networks. The unit offers an interface between firms, governmental bodies, and environmental organizations, and also often comprises a team that supports the development of synergies (Lowe 1997). The progression of industrial symbiosis networks is contingent on the organizational unit and the associated institution because they facilitate network embeddedness, strengthen the alignment between business and regulations, and help to coordinate transactions (Chertow and Ehrenfeld 2012). In other words, the organizational unit manages the business environment, including its uncertainty, munificence, and complexity (Aragón-Correa and Sharma 2003), thereby contributing to the environmental and the cooperative strategy of industrial symbiosis networks.

Consequently, we identify three dimensions of capabilities and resources that are relevant for industrial symbiosis networks on the level of the firm, the network, and the business environment: the proactive environmental stance of individual firms, cooperative relationships that entail network embeddedness and strategic alliances, and a business environment in which industrial symbiosis is institutionalized. We present the analysis of our data in Table 3.2 using these dimensions. Furthermore, we elaborate on our findings.

3.3.1 Individual firms – proactive environmental stance

The proactive environmental stance of firms implies seeking for innovative opportunities at the business/natural environmental interface (Sharma and Vredenburg 1998). This means that while firms are motivated to reduce waste and prevent pollution, they are looking for alternative forms of recycling outside their supply chain (Bansal and McKnight 2009). However, industrial symbiosis networks are often shaped by regulations that either directly address pollution prevention or indirectly create pressure by increased disposal or raw material costs.

Table 3.2: Capabilities and resources identified in industrial symbiosis networks

Industrial symbiosis	Individual firms – proactive environmental stance	Cooperative relationships – alliances and embeddedness	Business environment – institution and organizational unit
Kalundborg, Denmark	continuous and largescale by-product streams; integration of community perspectives on sustainable development; local plants with decision-making power	mutual interest in solving groundwater deficit; flexible synergies in terms of quality and quantity; historical social relationships and local communication ties; mutual trust in the problem-solving process	effective ways of operationalizing ideas based on synergies; environmental legislation and initiatives to save energy and water; flexible negation process between authorities and firms; institutionalized vision to make industry more compatible with nature;
Kwinana, Australia	secure availability and access to vital process resources; awareness of industrial operations and inputs and outputs; integration of initiatives to protect the sensitive local marine environment	major capital projects involving collective capacity expansion opportunities; historical supply chain integration occurred between industries prior to synergies	institutionalized form of air and water monitoring for the industries; fostering interactions between firms, government, and the public community; obstructive regulatory framework for using by-products
Barceloneta, Puerto Rico	shift to more in-facility reuse and recycling, which led to a collapse of sharing initiatives; fail to understand the local context and implicit public expectations	pooled needs and resources for waste treatment; established familiarity and trust; frequent interaction within the pharmaceutical industry;	the organizational unit provides an interface between governmental agencies and industries; it also facilitates interactions between firms and institutionalizes cooperative resource management
Styria, Austria	various and stable waste supply and demand as a result of divergent production programs; technological compatibility	mutual interest in waste recycling; easily observable quality criteria; sufficient number of potential partners; network atmosphere encourages trust and cooperation	firms are able to gain support from environmental NGOs via communication forums

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Industrial symbiosis	Individual firms – proactive environmental stance	Cooperative relationships – alliances and embeddedness	Business environment – institution and organizational unit
Guitang Group, China	life cycle thinking; supply chain integration; developing its own downstream companies to utilize nearly all by-products; integration of sugarcane farmers to stabilize supply	mutual interest with sugarcane farmers in increasing supply stability; supply chain actors share information and establish cooperation; technology center that developed techniques for by-product utilization	effective coordination of communication between enterprise units; close relationship with the local government; policies help to ensure a stable supply of by-products (bagasse and molasses);
Ulsan EIP, South Korea	continuously exploring synergistic opportunities based on previous experiences; increasing steam supply and demand	collective interest in increasing compatibility between operations; historical synergistic and other supply chain relationships	facilitate synergies with data and feasibility studies, social network establishment, and financial support; effective negotiation process; governmental subsidies; effective communication between national agencies
Tianjin Economic Development Area, China	developing technological innovations that use by-products as raw materials (water reclamation system and new soil sources); high demand on steam and hot water	mutual interest in restoring soil fertility around the industrial area;	disseminate information about industrial symbiosis; effective coordination and cooperation among different administrative divisions; supportive regulatory and economic instruments
Industrial Areas, United Kingdom	relative familiarity with one another's products and processes; issues with the continuity of supplies; small businesses are capable to transform their supply chain	managers are willing to share information and trust familiar partners	effective support for emerging synergies; expertise in analyzing synergy opportunities; connecting companies with synergy opportunities; knowledge base of firms in the region; governmental subsidies

Innovation is not necessarily radical in the sense that it is based on a set of new engineering and scientific principles opening up whole new markets and potential applications (Henderson and Clark 1990). Consequently, Henderson and Clark argue that the so called architectural innovation only reconfigures an established system by linking together existing components in new ways. The environmental strategy pursued in industrial symbiosis is characterized by a supply chain reconfiguration that connects (undesired) production outputs to material intake resulting in new material flows while eliminating others.

Connecting previously unrelated industries through a pipeline infrastructure that transfers excess energy in the form of steam or warm water is a typical form of industrial symbiosis. In Kalundborg, for example, the central power plant supplies steam and heat to the nearby oil refinery, pharmaceutical company, and the local municipality reducing their electricity intake (Jacobsen 2006). Furthermore, to reduce freshwater consumption, the power plant in turn reuses the wastewater and cooling water output of the refinery.

The power plant in Kalundborg also opted for a desulfurization process producing gypsum to meet environmental regulations because the adjacent plasterboard manufacturer was ready to purchase this by-product (Jacobsen and Anderberg 2004). Similarly, a pigment plant in Kwinana installed a secondary gas scrubber to maintain emission standards and produce an acid that is a valuable material substitute for another chemical plant (van Beers et al. 2007).

Waste and by-products are also converted into a market offering to avoid landfilling. The fly and bottom ash of power plants and incinerators, which would typically be landfilled, is for example used in cement production, brick and floor tile manufacturing, and in the production of organic fertilizers (e.g. Schwarz and Steininger 1997, Shi et al. 2010). Residual biomass is also used as organic fertilizer or converted to animal feed, thereby substituting (or complementing) artificial fertilizers and other sources of fodder (Jacobsen 2006).

From a technological point of view, supply and demand security (both quality and quantity) is vital for industrial symbiosis (Lowe 1997, Côté and Smolenaars 1997). In Kalundborg, continuous and stable by-product supply and demand are found to be critical factors of success (Jacobsen and Anderberg 2004). In the UK, issues with supply hindered industrial symbiosis projects (Paquin et al. 2014). Furthermore, technological compatibility between by-products and material intake is also an essential criterion for industrial symbiosis (Schwarz and Steininger 1997). However, modifying technical parameters, for example, in case of steam networking practices, is sometimes

necessary (Park and Park 2014).

In general, supply chain reconfiguration associated with synergistic transactions requires dedicated management with decision making power. In Kalundborg, the success of initiating synergies is attributed to autonomous plant managers who have been committed to the local alternative use of by-products and raw material substitutes for decades (Jacobsen and Anderberg 2004). Furthermore, it was found that smaller firms are capable to transform their business and reconfigure their supply chains in a relatively short time (Lombardi and Laybourn 2012). From a managerial perspective, reconfiguration requires surveillance and learning of other industries, benchmarking of technological alternatives, and the ability to accomplish the necessary internal and external transformations (Teece et al. 1997).

The proactive stance towards recycling involving industrial symbiosis requires an awareness that goes beyond the boundaries of the firm but still remains within geographical boundaries. The resulting knowledge pool of industrial operations and their associated material intake and outputs was found to be useful in the initiation of synergies in Kwinana (van Beers et al. 2007). Similarly, relative familiarity with one another's products and processes was found to be necessary in the NISP (Paquin et al. 2014). Knowledge about materials and wastes is often in the hands of employees who work next to the industrial processes. Consequently, ideas concerning industrial symbiosis often comes from employees who push waste and by-product issues higher up in the management hierarchy (Chertow and Ehrenfeld 2012).

In general, industrial symbiosis entails a cultural change, which has implications on how firms see themselves as part of a system (Lombardi and Laybourn 2012). This perspective integrates stakeholder perspectives and life cycle thinking (i.e. "the voice of the environment") into strategic management (Hart 1995). Consequently, firms often find further synergistic opportunities. Here, stakeholders are local suppliers and the local community of people where industrial operations take place. The role of additional stakeholders will be discussed later.

Responding to community expectations (and local governmental pressure) regarding the management of the local air- and watersheds and the protection of the sensitive marine environment was a dominant trigger for utility synergies in Kwinana (van Beers et al. 2007). The local chemical plant built an innovative nutrient-stripping wetland to reduce nitrogen discharges into the local bay. However, the idea of industrial symbiosis received negative publicity in Barceloneta when the local water treatment service received public complaints with regards to bad odors, respiratory ailments and pollution of

the local marine environment (Ashton 2011). Further investigations revealed poor testing, operational, and maintenance practices as primary causes. In this case, firms and stakeholders had clearly non-congruent expectations regarding the environmental strategy.

Supply chain integration is another opportunity for industrial symbiosis. The Guitang Group is an integrated enterprise that turns production to a closed loop ecosystem by integrating pulp and paper, alkali recovery, cement, and alcohol plants around sugar refining (Zhu and Côté 2004). The core competence of the group is reflected in a life cycle perspective on its production system. The group takes care of the by-products of its sugar production (bagasse and molasses) and also the residues of the subsequent production units. The group also integrates sugarcane farmers in the system by providing them a fertilizer made of alcohol residue. The advantage of the system is its diverse product portfolio and the synergies between production units that minimize waste disposal and reduce plantation costs of sugarcane (Zhu et al. 2007).

We conclude that firms in industrial symbiosis require stable and continuous supply and demand of high-quality undesired production outputs within relative geographical boundaries. Furthermore, we conclude that firms in industrial symbiosis draw on extensive employee involvement and tacit supply chain management skills, as well as on life cycle thinking and proactive stakeholder management while finding suitable opportunities for by-product reuse.

3.3.2 Cooperative relationships – strategic alliances and network embeddedness

Firms in industrial symbiosis networks emphasize community relationships, cooperation, and connectedness (Bansal and McKnight 2009). In general, firms that are embedded in the same social network (community) are likely to have a shared understanding of certain issues and to develop a similar behavior in responding to those issues (Gulati 1998). Additionally, familiarity between partnering firms breeds trust around the norm of cooperation, and network embeddedness provides firms with information about each other's needs and requirements (Gulati 1995, 1998). Consequently, the network in which firms are embedded defines alliance opportunities (Gulati 1999).

Industrial symbiosis networks often emerge as result of facing natural resource scarcity in a certain region. For instance, in Kalundborg and Barceloneta, companies faced water deficits (Jacobsen 2006, Ashton 2011), companies in the Tianjin Economic Development Area (TEDA), China, faced severe land degra-

dation (Shi et al. 2010), and in Styria, firms had mutual interest in solving waste recycling (Schwarz and Steininger 1997). These issues were addressed with joint action partly resulting in industrial symbiosis projects. Furthermore, in Kwinana, major capital projects served as a regional synergy driver (van Beers et al. 2007). The new iron smelter in the area created opportunities to source a number of inputs locally, such as lime kiln dust and wastewater, and also provided outputs with potential reuse, such as slag and gypsum.

In general, strategic alliances require some degree of familiarity between the partners (Gulati 1995, 1999). In Kwinana and Ulsan, for example, historical supply chain integration took place locally establishing social ties between firms before the development of regional synergies (van Beers et al. 2007, Park et al. 2008). In Barceloneta, the intra-industrial network of pharmaceutical firms led to industrial symbiosis projects (Ashton 2008). In Kalundborg, however, structural embeddedness developed through regular community interactions (Jacobsen and Anderberg 2004). In industrial symbiosis networks, embeddedness is described with a unique “atmosphere” and a “short mental distance” that associates with trust and shared norms of cooperation (Ehrenfeld and Gertler 1997, Schwarz and Steininger 1997).

Cooperation in industrial symbiosis networks prompt firms to go beyond market transactions and make specific investments related to by-product reuse and share knowledge (information and know-how) while seeking synergistic opportunities. Consequently, inter-firm relation-specific assets are developed, and firms become involved in inter-firm knowledge-sharing routines (Dyer and Singh 1998).

In relation to synergistic projects, firms typically invest in treatment operations, infrastructure or facilities, capacity expansion, process improvement, or product development. In Kalundborg, investments in the pipeline infrastructure and technical installations exhibit the cooperative nature of companies (Jacobsen 2006). Similarly, companies in Barceloneta, in Ulsan, and the TEDA made joint investments in utility synergies including steam and water exchanges (Shi et al. 2010, Behera et al. 2012, Ashton 2008).

Furthermore, industrial symbiosis networks take advantage of knowledge transfer and integration because these are potential sources of innovation. For example, the Guitang Group has a dedicated technology center that is in collaboration with universities researching alternative by-products and new ways of improving by-product utilization (Zhu et al. 2007). The group also invested in synergy projects with other sugar refinery groups combining its technological expertise with the others’ bagasse supplies (Zhu and Côté 2004). In Kalundborg, symbiosis specific problem-solving routines are employed that

provide effective ways of operationalizing project ideas (Jacobsen and Anderberg 2004).

However, the essence of partnerships in industrial symbiosis is complementarity between resources, which results in a synergistic effect whereby resources (e.g., undesired production outputs) become more valuable than they had been before they were combined (Dyer and Singh 1998). In a certain geographical proximity, this implies unique fit between firms which they take advantage of (Bansal and McKnight 2009). Firms typically lose their interest in industrial symbiosis if complementarity doesn't longer exist. For example, a firm may develop its in-house recovery process rendering its partner unnecessary (Ashton 2009); a firm may find a more profitable way of using its by-product or even eliminate by-products with cleaner production technologies (Shi et al. 2010).

Furthermore, synergistic relations define interdependency among firms. In Kalundborg, increased interdependency did not lock-in firms to the region, instead the synergies have changed both in terms of quality and quantity over the decades (Jacobsen and Anderberg 2004). However, interdependency is seen as a potential threat to industrial symbiosis networks: losing a critical by-product supply or market can be disastrous for a firm and failure can propagate through the network (Lowe 1997, Bansal and McKnight 2009). Consequently, to overcome fragility, the Guitang Group aims to diversity in its by-product portfolio and increase supply chain redundancy with multiple bagasse suppliers (Zhu and Côté 2004). However, such increased resilience leads to additional complexity and coordination challenges.

In relation to cooperation, we conclude that firms in industrial symbiosis networks leverage familiarity and emphasize collective issues embedded in their social network (community). Furthermore, firms in industrial symbiosis networks draw on experience in complementary strategic alliances and on the efficient management of interdependencies, as well as on symbiosis-specific knowledge transfer routines.

3.3.3 Business environment – institutionalization and organizational unit

One of the key features of industrial symbiosis is that firms are in a business environment that supports the development of symbiotic relations (Bansal and McKnight 2009). In fact, industrial symbiosis networks are more than a number of actors engaging in dyadic waste relationships; there is a conscious recognition and intentional pursuit of network benefits combined with an institutionalization of beliefs and norms enabling collaborative behavior

(Chertow and Ehrenfeld 2012). In industrial symbiosis networks, institutionalization often manifests in an organizational unit. Typically, the unit comprises firms and stakeholders including authorities, non-governmental organizations, and a recruiting team (Lowe 1997). In general, the institution establishes a supportive context and offers management services for the industrial symbiosis network (Schwarz and Steininger 1997, Chertow and Ehrenfeld 2012)

Part of the institutional conditions relate to public authorities and a legislative context that enables and drives industrial symbiosis. For example, in Kalundborg, the flexible Danish environmental legislation facilitated local problem solving (Jacobsen and Anderberg 2004). In the Guangxi region, environmental legislation prohibits the disposal of bagasse and molasses, and thus encourages small sugar refineries to deliver these by-products to the Guitang Group (Zhu and Côté 2004). However, obstructive regulations create a barrier for industrial symbiosis. In Kwinana for example, firms experience difficulties in getting governmental approval for alternative use of fuels and raw materials (van Beers et al. 2007). In an effort to alleviate legislative complications, the European Commission also recently proposed to clarify rules on by-products to facilitate industrial symbiosis (EC 2015).

Furthermore, governments contribute to the development of industrial symbiosis with financial instruments, such as disposal fees and subsidies. In general, disposal costs are effective if they exceed the operational and transaction costs of industrial symbiosis. In fact, waste disposal costs are the most common trigger of industrial symbiosis (Jacobsen 2006, Paquin and Howard-Grenville 2012, Yu et al. 2014). Additionally, governmental subsidies also incentivize industrial symbiosis. Typically, infrastructural developments in centrally planned industrial symbiosis networks are subsidized (Behera et al. 2012, Paquin and Howard-Grenville 2012, Yu et al. 2014).

Generally speaking, the institutional structure, including regulations, disposal costs, and subsidies, is contingent to industrial symbiosis. In other words, the business environment supports the development of industrial symbiosis networks. However, besides governmental munificence, the general business environment is also affected by organizational uncertainty and complexity (Aragón-Correa and Sharma 2003).

The institutionalization of industrial symbiosis reduces organizational uncertainty and complexity in industrial symbiosis networks. For example, the Symbiosis Institute in Kalundborg developed as collective sense of industries, local authorities, and environmental agencies with a vision to make industry more compatible with nature (Jacobsen and Anderberg 2004). As a result, a set

of common values and beliefs have evolved, and the symbiosis projects were taken to the level of multilateral cooperation. In Barceloneta, the Wastewater Advisory Council became the institution of cooperative resource management that engaged firms in industrial symbiosis

citepAshton.2011. Similarly, the Kwinana Industrial Council addresses issues common to the industries in the region, and seeks to foster positive interaction between firms, the government, and the broader community (van Beers et al. 2007).

The organizational unit facilitates industrial symbiosis networks by offering services that reduce the associated costs of industrial symbiosis. These services typically include data collection and coordination tasks. Consequently, the organizational unit increases the ability of the industrial symbiosis network to accumulate, store, and diffuse symbiosis-specific information, such as material flow data and waste legislations. Furthermore, coordination tasks in relation to industrial symbiosis include social network establishment and the effective management of transactions.

In centrally organized industrial symbiosis networks, data collection typically focuses on material flows within geographical boundaries, such as industrial districts and geographical regions. For example, the NISP collects and analyses data about material flows in different regions in the UK (Paquin and Howard-Grenville 2012). Similarly, in Korea and China, the organizational units collect information in industrial districts, such as the Ulsan eco-industrial park and the TEDA (Behera et al. 2012, Shi et al. 2010). The point of data collection is to analyze emissions, and identify feasible synergy opportunities. Feasible opportunities are then further supported by the organizational unit.

The coordination task in case of central organization often starts with facilitating social networking and connecting firms with potential synergies. Engaging firms in interaction is a challenge when firms are not aware of the industrial symbiosis initiative (Park and Won 2007). Effective recruitment, however, relies on boundary spanner personnel (project champions) who are trusted by industry representatives, and have personal networks (Paquin et al. 2014).

Furthermore, effective management facilitates discourse between the industrial symbiosis network and the governments. For example, in the TEDA, the administrative commission has been a lean interface between firms and the local and national governments allowing effective coordination and co-operation (Shi et al. 2010). Furthermore, transaction costs are mitigated by the organizational unit. In Ulsan, for example, the administration offers a

	Individual firms	Cooperative relationships	Business environment
Capabilities	<ul style="list-style-type: none"> • awareness of inputs and outputs of other industrial operations • ability to reconfigure the supply chain and supply chain integration • life cycle thinking and proactive stakeholder management 	<ul style="list-style-type: none"> • experience in complementary alliances • managing interdependence of synergistic relations • symbiosis-specific knowledge transfer routines 	<ul style="list-style-type: none"> • engage firms in the institution of industrial symbiosis • ability to moderate administrative hurdles • effective coordination of synergistic transactions
Resources	<ul style="list-style-type: none"> • stable supply of high-quality effluents and solid wastes • stable demand on such undesired production outputs 	<ul style="list-style-type: none"> • mutual interest in solving common issues • familiarity and trust among firms 	<ul style="list-style-type: none"> • supportive legislation and financial instruments • information system compiling industrial symbiosis related data

Figure 3.1: Capabilities and resources relevant for the three managerial dimensions of industrial symbiosis networks.

business framework and supports negotiation to ensure collective benefits to participants (Behera et al. 2012).

In relation to the business environment, we conclude that institutionalization creates a business context that supports industrial symbiosis with regulatory and financial instruments. Furthermore, the organizational unit reduces uncertainty and complexity in the business environment of industrial symbiosis networks by engaging firms, providing symbiosis-specific information, and effectively coordinating transactions.

Figure 3.1 concludes our findings about the key capabilities and resources in industrial symbiosis networks.

3.4 Competitiveness in industrial symbiosis

Firms in industrial symbiosis capitalize on unique opportunities afforded by geographical proximity, excess resources, and potentially useful wastes; consequently, resulting in idiosyncratic supply networks (Bansal and McKnight 2009). Environmental strategies pursuing industrial symbiosis create value by, for example, increasing resource productivity, generating revenue, reducing costs, and mitigating risk. Furthermore, a strategy based on industrial symbiosis is arguably rare because of its uniqueness. Consequently, industrial symbiosis generates competitive advantage.

Furthermore, industrial symbiosis is difficult to initiate and maintain due to the tight integration among a diverse set of organizations (Bansal and McKnight 2009). We argue that industrial symbiosis networks are imperfectly imitable because of the combination of the previously identified capabilities and resources that feed into supply chain management (Barney 2012). We attribute

these capabilities and resources to three dimensions: the proactive environmental stance of the firm, the management of cooperative relationships, and the business environment. In this section, we will now theorize how firms obtain sustained competitive advantage during the initiation and progression of industrial symbiosis networks.

3.4.1 Initiating industrial symbiosis

To initiate industrial symbiosis, firms need to challenge their established disposal and procurement practices, learn about alternative material flows and configurations, and set out to reconfigure part of their existing supply chains. Firms may find business opportunities by learning about unsatisfied needs for material flows in their surroundings that may be supplied with their own undesired production outputs. Likewise, through their insight in material flows in the region, firms may also identify potential alternatives to their own intake of resources. Consequently, a firm that systematically aims to turn waste to resource, surveys the market for opportunities, and has a willingness and financial capacity to engage in new transactions is more likely to initiate industrial symbiosis.

In general, reconfiguration requires to go beyond existing communication channels, information filters, and managerial routines (Henderson and Clark 1990). Firms that initiate industrial symbiosis have to engage in communication outside their core business activities. As a result, potential partners come into the view of each other in a form of architectural knowledge of material flows in their surroundings. Furthermore, it is necessary to allow undesired production output related issues to filter into the level of strategic management. Additionally, firms need to internalize the management of communication and information filters related to industrial symbiosis in order to become effective in reconfiguration.

Similarly to other pollution prevention strategies, the initiation of industrial symbiosis is people intensive (Hart 1995). It relies on skilled personnel that is able to integrate cross-functional knowledge, and dedicated management that brings new architectural knowledge into effective action. Furthermore, it combines proactive environmental management capabilities with supply chain reconfiguration. Therefore, the initiation of industrial symbiosis is causally ambiguous (tacit) and is hence imperfectly imitable.

PROPOSITION 1. Firms that systematically aim to turn undesired production output into a resource and invest in learning about material flows in their surroundings; furthermore, possess the necessary financial resources, tacit knowledge, and managerial

capabilities to reconfigure their supply chain obtain competitive advantage in industrial symbiosis.

Implementing industrial symbiosis carries social challenges associated with the personal relationships and technical challenges pertain to the quantity and appropriate quality of industrial by-products (Bansal and McKnight 2009). Consequently, those partners who trust each other and are able to secure by-product supply and demand are more likely to initiate industrial symbiosis.

Strategic alliances often depend on a firm's ability to find a partner with a relational capability (i.e. a firm's willingness and ability to partner) and complementary strategic resources (Dyer and Singh 1998). In case of industrial symbiosis, relational capabilities endow individuals in key positions to start subject-oriented inter-firm dialogue, to develop and spread ideas, and develop the skills to convince opponents (Schwarz and Steininger 1997, Jacobsen and Anderberg 2004). However, network embeddedness, meaning that potential partners know each other's needs, requirements, and trustworthiness, serves as a basis for those individuals. Therefore, the initiation of industrial symbiosis is socially complex and thus difficult to imitate.

Technical challenges also need to be overcome. In general, firms with stable and continuous by-product supply or demand are more likely to be found as a partner. Furthermore, a firm that is able to meet its partner's quality standards without (or with minimal) by-product treatment is more likely to initiate industrial symbiosis because the anticipated coordination costs and appropriation concerns are lower. For instance, it is easier to find a partner for fly ash without metal contaminants. However, uneven quality of by-products could cause damage to equipment or quality of products (Lowe 1997).

Residual disposal or procurement costs occur if there is a mismatch in by-product supply-demand. In this case, partners face additional transaction costs for procuring the remaining raw materials and/or for disposing by-product leftovers. Consequently, matching by-product supply-demand in industrial symbiosis is valuable and also imperfectly imitable because of partner scarcity in close geographical proximity.

PROPOSITION 2. Firms with managers that have relational capabilities to engage other firms in by-product transactions have competitive advantage in industrial symbiosis. Furthermore, by-product transactions based on high-quality production outputs and with matching supply and demand obtain competitive advantage.

The degree to which the general business environment supports proactive environmental strategies is contingent to industrial symbiosis (Aragón-Correa and Sharma 2003). Regulations regarding waste reuse allowance or subsidiza-

tion have a critical role in the initiation of industrial symbiosis, while business environments where waste reuse is regulated typically inhibits industrial symbiosis. Additionally, local communities and external stakeholders are demanding companies to become more visible and transparent (Freeman 1984, Hart 1995). Information disclosure about undesired production outputs is also necessary to learn about synergistic opportunities. In general, the organizational unit offers a communication platform between firms and governments, supporting the business environment.

Furthermore, industrial symbiosis is contingent upon certainty in the business environment. Organizational effect uncertainty arises from a lack of organizational capabilities and resources and generally inhibits proactive environmental strategies (Aragón-Correa and Sharma 2003). However, the organizational unit of industrial symbiosis mitigates this uncertainty by institutionalizing cooperation and coordination between firms and external stakeholders. The organizational unit embodies a sense of community in terms of a general attitude towards economic and environmental development. Additionally, the organizational unit often offers managerial routines for material flow mapping, feasibility studies, and matchmaking for companies that are in a lack of these capabilities, and also ensures rules and principles for cooperation that reduce the associated cost of initiating industrial symbiosis.

In general, the institutional business environment that is able to control opportunism and encourage cooperative behavior is socially complex (Dyer and Singh 1998). Consequently, the business environment of industrial symbiosis is difficult to imitate.

PROPOSITION 3. In a business environment that supports the reuse of production outputs with regulatory and financial instruments, firms are more likely to initiate industrial symbiosis. Furthermore, firms that support an organizational unit where the norms of cooperation are institutionalized and they can have discourse with authorities obtain competitive advantage.

3.4.2 Progressing industrial symbiosis

Research found that industrial symbiosis networks that persist move in the direction of environmental sustainability (Chertow and Ehrenfeld 2012). However, a synergy is not good in itself if the technology upstream is not sustainable (Lowe 1997). For example, a fossil fuel-based power plant providing steam to an oil refinery is still contributing to the depletion of non-renewable resources (coal, oil and natural gas) upstream (Mirata 2004). Moreover, synergistic transactions could lock in continued reliance on toxic materials and on

unsustainable technologies (Lowe 1997). In other words, an industrial symbiosis that has short-term financial gains can turn out to be a competitive disadvantage in the future.

In general, firms that engage in industrial symbiosis benefit from life cycle thinking and stakeholder integration. However, these capabilities require socially complex resources, involving fluid communication across functions, departments, and organizational boundaries (Hart 1995). Consequently, integrated enterprises, such as the Guitang Group, have competitive advantage because management is able to gradually expand and coordinate the industrial symbiosis network effectively emphasizing the entire life cycle of production.

Furthermore, a proactive environmental strategy that is supposed to exclude toxic materials and minimize the use of nonrenewable resources also needs to use renewable resources in accordance with their rate of replenishment (Hart 1995). Competitive advantage can be achieved by gaining preferred or exclusive access to important, but limited resources (Hart 1995). Consequently, firms in industrial symbiosis can preempt competition by tapping into by-product supply or demand and fully utilize what is available. In industrial symbiosis, this first-mover advantage can be completed while progressing toward matching supply and demand.

PROPOSITION 4. Firms that have the organizational ability to coordinate functional groups within the firm and to integrate the perspectives of stakeholders have competitive advantage in industrial symbiosis. Furthermore, firms that secure their exclusive access to by-product supply or demand obtain competitive advantage in industrial symbiosis.

Firms in synergistic relations face interdependencies that create challenges. However, interdependencies can also be a source of competitive advantage. One way to increase imperfect imitability of a relationship is to increase the proportion of synergy sensitive resources (Dyer and Singh 1998). For example, in Ulsan, a chemical company increased its steam consumption capacity by building additional plants, while a partnering incinerator changed its boiler design to be able to produce high pressure steam to the plants (Park and Park 2014). The chemical plant showed substantial interest to tap into all available steam resources in its area, and the incinerator exhibited increased flexibility in providing a market offering. The two firms gradually deployed the expansions creating conditions that made subsequent, specialized investments economically viable. The resulting enhanced inter-organizational asset interconnectedness is imperfectly imitable because its full potential lies in a bundle of investments (Dyer and Singh 1998).

In industrial symbiosis, relations can be a source of knowledge transfer and integration. In general, the ability to exploit outside source of knowledge is a function of prior related knowledge. Partner-specific absorptive capacity is a firm's ability to recognize and assimilate valuable knowledge from a particular alliance partner (Dyer and Singh 1998). In industrial symbiosis, firms are able to develop partner-specific absorptive capacity by emphasizing symbiosis-specific knowledge transfer and integration routines. Consequently, firms extend their overlapping knowledge base and increase the likelihood to identify additional synergy opportunities. For example, in Kalundborg, high level absorptive capacity of the firms enables collaboration on new technological solutions within the framework of industrial symbiosis. In general, partner-specific absorptive capacity is imperfectly imitable because it is relation-specific and evolves over time (Dyer and Singh 1998).

PROPOSITION 5. Firms that increase the proportion of synergy-sensitive resources and/or operations in synergistic relations obtain competitive advantage. Furthermore, firms that develop partner-specific knowledge absorption capacity in synergistic relations obtain competitive advantage.

The progression of industrial symbiosis networks entails broader by-product markets. These larger networks will give greater resilience to the pattern of trades; however, their complexity raises with the increasing number and diversity of members (Lowe 1997). As a result, coordination challenges are intensified both in terms of collective effort to environmental sustainability and managing transactions. Ideally, in larger industrial symbiosis networks a dedicated team in the organizational unit takes care of coordination.

The organizational unit needs to have a clear vision, as well as environmental and community values and performance objectives that consider the resources and boundaries of the network (Lowe 1997). In fact, sustainable development requires a shared vision and consensus about low-impact technologies (Hart 1995). Consequently, to deliver performance, the organizational team has to be able to communicate environmental and community values, and to engage companies in pursuing the vision of sustainability. However, collective dedication to a shared vision in relation to sustainability is difficult to achieve in complex business environments (Aragón-Correa and Sharma 2003). In other words, the collective effort to environmental sustainability and thus the progression of industrial symbiosis networks is a socially complex task that is specific to the individual networks.

The other coordination task of the organizational unit, managing transactions in the industrial symbiosis network, includes filling critical supply and demand niches while ensuring consensus among the members regarding mu-

tual benefits (Lowe 1997). Large industrial systems typically consist of a diverse and dynamic set of firms. Therefore, an industrial symbiosis network needs flexible management in order to include the various production outputs of industrial systems. Furthermore, continuously filling supply and demand also requires a certain amount of redundancy in particular when small firms with inconsistent production are involved. However, collective benefits shared among network members potentially harm individuals. Consequently, a notion of fairness has to be established. In general, managing diversity and redundancy, and ensuring mutual benefits are socially complex, and require tacit (causally ambiguous) managerial skills.

PROPOSITION 6. In industrial symbiosis networks, an organizational unit that communicates environmental and community values, and develops consensus about low impact-technologies reduces complexity and facilitates progress. Furthermore, in industrial symbiosis networks where diversity and redundancy is managed effectively and fair benefits are ensured firms obtain competitive advantage.

3.5 Conclusion

Industrial symbiosis is a supply chain strategy based on cooperative relationships that connect the supply of undesired production outputs with unsatisfied needs for material flows. The resulting synergies reduce waste disposal and virgin material intake, and it is a key feature of industrial ecosystems (Frosch and Gallopoulos 1989). Industrial symbiosis is a network phenomenon emphasizing community, connectedness, and collaboration within geographical proximity (Bansal and McKnight 2009). More importantly, there is competitive advantage attributed to industrial symbiosis relations reflected in increased productivity, innovative product or process changes, increasing revenue, diversifying business, and managing risk (Porter and van der Linde 1995, Lombardi and Laybourn 2012). There are significant environmental and community-related benefits attributed to industrial symbiosis; however, the attributed competitive advantage is what makes it attractive for most businesses (Chertow 2000).

This paper contributes toward a theory of competitiveness in industrial symbiosis in order to provide theoretical grounding for the previous arguments concerning competitive advantage. To do so, the paper presents a resource-based view of industrial symbiosis and the related supply chain phenomenon. To be able to include the level of the firm, the network, and the business environment, three extensions of the general resource-based view are used: the natural-resource-based view of the firm (Hart 1995, Hart and Dowell

2011), the relational view (Dyer and Singh 1998), and the contingent resource-based view (Aragón-Correa and Sharma 2003). The paper draws on eight published cases of industrial symbiosis networks worldwide, to inductively build theory from existing cases (Eisenhardt and Graebner 2007). The selected cases have also been surveyed recently by other researchers for developing theory on industrial symbiosis (Chertow and Ehrenfeld 2012). Therefore, they are believed to represent the features of industrial symbiosis, and to form a solid basis for this particular research.

The first contribution of the paper is the identification of key organizational capabilities and resources relevant in industrial symbiosis. In fact, three dimensions are identified: the proactive environmental stance of individual firms; the cooperative relationships, including strategic alliances and network embeddedness; and the general business environment, including institutionalization and an organizational unit that are contingent to industrial symbiosis. Consequently, it is suggested that industrial symbiosis networks entail firm-specific and relation-specific capabilities and resources that are moderated by capabilities and resources present in the business environment.

The second contribution of the paper is its elaboration on how firms may obtain sustained competitive advantage in industrial symbiosis. The paper considers initiation and progression as two distinct stages of industrial symbiosis networks. Furthermore, it incorporates the previously identified dimensions of capabilities and resources. It theorizes that industrial symbiosis networks are difficult to imitate because initiation draws on tacit personnel skills, faces partner scarcity, and involves institutionalization; and progression requires life cycle thinking, inter-organizational asset interconnectedness, and an organizational unit that coordinates the sustainability effort and the transactions in the network. The findings are expressed in six propositions that constitute the basis for a theory of competitiveness in industrial symbiosis networks.

In conclusion, this paper contributes toward a theory of industrial symbiosis from a management point of view. However, the resource-based view used in this paper combining three managerial dimensions can also be a useful tool for future researchers studying other supply chain or network phenomena. Furthermore, the results have significant managerial implications because they emphasize important capabilities and resources for sustainable development, and they suggest practicalities for obtaining competitive advantage in industrial symbiosis networks. Future research, however, should test these propositions.

CHAPTER 4

Fair resource allocation strategies

This chapter is based on a manuscript to be submitted for publication under the title “The price of fairness in industrial symbiosis networks”. The manuscript is co-authored by Gábor Herczeg and Renzo Akkerman.

Abstract

In this paper we address collaborative efforts in by-product synergies as seen in industrial symbiosis networks. We propose a mathematical framework to model fair resource allocations for multiple, concurrent by-product suppliers with limited by-product demand. We analyze the price of fairness resulting from different gain-based and loss-based allocation strategies. We find that these allocation strategies lead to different requirements in terms of information sharing, and show how the resulting price of fairness depends on characteristics of the by-product synergy system. Furthermore, we find that while allocation strategies based on equal and equal marginal profits and costs motivate collaboration, strategies based on proportionality reward individualistic behavior.

4.1 Introduction

The efficient use of natural resources is a key part of sustainable development. The reuse of industrial waste and by-products offers opportunities to reduce raw material consumption and avoid the consequences of disposal. When performed across company borders, such reuse activities are referred to as industrial symbiosis. Industrial symbiosis is recognized and promoted as an important tool for sustainable development. For instance, the Organization for Economic Co-operation and Development (OECD) includes industrial symbiosis in their discussion of eco-innovation, i.e. new ways of addressing environmental problems and decreasing energy and resource consumption, while

promoting sustainable economic activity (OECD 2012). The European Commission shares this perspective, and attributes key importance to industrial symbiosis in achieving resource-efficient circular material flows in Europe (EC 2011, 2015). At the same time, the knowledge base to support businesses and policy makers in these developments is limited, and more information is needed to be able to make informed decisions (EEA 2016).

The idea of industrial ecosystems as a strategy for manufacturing was identified by Frosch and Gallopoulos (1989), and has led to significant discussion of the industrial symbiosis phenomenon in the industrial ecology community. In recent years, industrial symbiosis and related concepts also started receiving attention in the operations management community (Bansal and McKnight 2009, Lee 2012), where it can be characterized by a network of collaborating organizations based on by-product flows (Bansal and McKnight 2009). Matching the supply and demand of these by-products, however, can be challenging since they are side effects of other production activities. Consequently, demand and supply mismatches are common, leading to the disposal of excess by-product and the procurement of supplementary virgin raw materials. Also, it can lead to the identification of additional uses for by-products, or the sourcing of by-products from multiple sources (e.g. Schwarz and Steininger 1997, Zhu and Côté 2004).

In this paper, we specifically focus on the use of by-products from multiple sources. Next to a way to avoid mismatches in supply and demand, concurrent by-product reuse is also an operational strategy to increase supply resilience, since the discontinuation of a certain by-product flow in industrial symbiosis networks could otherwise lead to critical supply problems (Lowe 1997). The management of by-product supply from multiple, concurrent sources can however lead to a resource allocation problem, in which the limited by-product demand has to be allocated to the suppliers. Since a fair distribution of costs and benefits from by-product reuse is a key characteristic of industrial symbiosis (Lombardi and Laybourn 2012), the demand allocation needs to include fairness considerations. Here, we need to realize that “fair” does not necessarily mean equal (Benkler 2011), and that fairness normally comes at a cost, which is the trade-off for emphasizing collective gains or losses instead of an economically optimal allocation (Bertsimas et al. 2011).

Industrial symbiosis initiatives are often supported by a matchmaking broker or a central organizational unit. Activities of such supporting organizations involve matchmaking of symbiotic relationships and mediating by-product supply and demand, and therefore also have to consider collective economic incentives for the participants in order to engage them in collab-

oration (Lowe 1997). This also includes the consideration of resilience and fairness in the industrial symbiosis network.

The aim of this paper is to study the consideration of fairness in concurrent by-product reuse in industrial symbiosis networks. We introduce a minimal formal model of an industrial symbiosis network, allowing us to easily derive the by-product allocations and the price of fairness for allocation strategies with different fairness considerations. More importantly, we use these basic analytical results to provide insights on requirements and consequences of engagement in the considered industrial symbiosis network under the different fairness considerations. This includes the identification of the allocation strategy with the lowest price of fairness, the information sharing requirements for the different strategies, as well as the incentives that suppliers have in the resulting situation to reduce waste, increase reuse efficiency, or to share technological advantages. The results and discussion lead to insights that are relevant for companies collaborating in industrial symbiosis, as well as for supporting organizations and policy makers.

In the following, we first briefly discuss related literature, after which we introduce our model of a by-product reuse system with two concurrent suppliers and one buyer. We then derive analytical expressions for the allocation quantities and the price of fairness for several fairness-oriented allocation strategies. We then use these results in a comprehensive numerical study, followed by a discussion section focusing on the implications of the analytical and numerical results. Finally, we conclude our paper, discuss the limitations of our study, and provide directions for further research.

4.2 Related literature

The paper draws on several streams of academic literature. First, our work builds on research that deals with the operations management aspects of industrial symbiosis. Secondly, our work relates to resource allocation and the impact of fairness considerations. In the following, we briefly discuss these two streams of literature.

4.2.1 Industrial symbiosis in operations management

By-products occur in production systems, especially in process industries where divergent product streams are common. In general, by-products have low economic value and may need to undergo additional treatment in order to be sold or reused (Flapper et al. 2002). In many cases, by-products are therefore disposed of, but they are also used as alternative raw materials for an end

product or in the production of new end products (French and LaForge 2006). This reuse phenomenon is also referred to as by-product synergy (Chertow 2000, Lee 2012).

In industrial symbiosis, by-products are procured from external source(s) and the transactions engage companies in a specific kind of buyer-supplier interdependency (Bansal and McKnight 2009). Input-output matchmaking services bring people and organizations together to stimulate participation, help to identify by-product synergy opportunities, and initiate and coordinate activities (van Beers et al. 2007, Chertow 2007). A matchmaking broker (mediator) finds complementary by-product supply and demand, for example through pooling by-product suppliers to create flows sufficient to market, and maintains the cohesion of a broader synergy system (Lowe 1997, Paquin and Howard-Grenville 2012). Here, two major challenges are to meet quality and quantity expectations in the by-product transaction, which typically is organizationally subordinate to the primary production activities (Bansal and McKnight 2009).

According to Lowe (1997), industrial ecosystems built on symbiotic relationships are subject to failure of critical synergies. Researchers also argue that a broader by-product market gives resilience to the synergies, maintaining alternative suppliers and buyers to step in when business conditions change (Lowe 1997, Zhu and Côté 2004, Paquin and Howard-Grenville 2012). However, Zhu and Côté (2004) point out that increasing the number of suppliers and buyers also raises supply chain barriers as it comes with organizational complexity and potentially higher costs. This can lead to a too high efficiency loss (Pettit and Fiksel 2010).

From an operations management perspective, designing a resilient supply chain reduces risk of failure associated with supply and demand disturbances (Christopher and Peck 2004, Pettit and Fiksel 2010). An increased supplier base increases flexibility and reduces the risk of supply chain disturbances (Jüttner et al. 2003). On the other hand, the excess capacity conflicts with an efficiency focus (Jüttner et al. 2003). Pettit and Fiksel (2010) proposed that supply chain performance improves when capabilities and the actual vulnerabilities to risks are more balanced. In short, supply chain redundancy improves resilience, but after a certain level it is unjustified.

Interdependency, supply and demand disturbances, as well as market growth and product criticality motivate supply chain collaboration (de Leeuw and Fransoo 2009). de Leeuw and Fransoo (2009) also point out that supply chain collaboration is characterized by aspects such as long-term business relationships, common objectives, and cooperation (e.g., information sharing

and joint operations management). Such collaborative approaches are by definition present in (regional) industrial ecosystems, which are communities of businesses that collaborate with each other to efficiently share resources (e.g., information, technologies, utilities, materials, institutions), leading to collective, equitable gains and increased employment (Lambert and Boons 2002, Baas and Boons 2004). Accordingly, Lombardi and Laybourn (2012) argue that industrial symbiosis must provide fair, but not necessarily equal benefits for the participating companies.

It is clear that industrial symbiosis coordination aims to efficiently match by-product supply and demand, while also creating a resilient synergy system. In this respect, the effective allocation of by-products between multiple and concurrent suppliers and buyers is an important consideration. It manages resilience and ensures collective economic incentives for the participating companies as well as prospect for future growth of by-product utilization.

4.2.2 Resource allocation and fairness

Resource allocation has been studied extensively, also in relation to fairness considerations. Most work has its origins in the economic concepts of justice and equity in cooperative settings (Rawls 1999), as well as psychological work on self-interest and altruism (Rabin 1993).

With regards to operations and supply chain management, fairness is often considered in supply chain collaboration (Stadtler 2009). Important applications can be found in the allocation of bandwidth in communications networks (Kelly et al. 1998), and in a manufacturer's allocation of a limited supply of products to retailers (Kumar et al. 1995). Fair resource allocation can be based on different approaches. It requires some kind of fairness measure, which is mostly related to gains or losses, i.e. profits or costs (Hougaard 2009, Stadtler 2009). Here, sharing losses could also be considered reducing unfairness.

Various allocation rules have been developed and studied over the years, often based on order sizes or past sales (Hall and Liu 2008). In fact, a plethora of fairness principles regarding resource allocation has been proposed in the operations literature and been recently reviewed by Bertsimas et al. (2011). Generally, allocation rules require an understanding of what is considered fair, often linked to equality or proportionality to some other system characteristic (Cachon and Lariviere 1999, Harks and Miller 2011).

In order to employ fair resource allocation, information about the suppliers' available quantities and their cost structures needs to be incorporated in the fairness strategies (Stadtler 2009). There might be information asymme-

try between the supply chain members, and the establishment of an efficient or fair allocation might depend on information sharing (Li 2002). Usually, the fairness is considered by a central decision maker or a mediator, who should then also possess the necessary information (Stadtler 2009, Bertsimas et al. 2011).

A common characteristic of introducing fairness in resource allocation is that the resulting allocation leads to some kind of efficiency loss. This is the difference between the maximum system efficiency and the efficiency under a fair allocation (Bertsimas et al. 2011). In case of multiple suppliers, this trade-off is relevant when one supply chain is more efficient and economically favourable compared to the other. This economic trade-off is referred to as the price of fairness, as introduced by Bertsimas et al. (2011). The price of fairness is normally expressed as a percentage efficiency loss compared to the optimal (economic) efficiency of the system (Bertsimas et al. 2012).

As Tijs and Driessen (1986) already pointed out, there is no final best allocation, as this depends too much on the context in which the allocation problem arises. However, for the specific context of industrial symbiosis, we are able to provide insights on the performance of various resource allocation rules, especially in relation to their price of fairness.

To be able to do this, we develop a framework for a by-product synergy system with two concurrent suppliers. Furthermore, we take the perspective of a broker (mediator) who is entitled to propose allocation rules resulting in fair gains or losses in the by-product synergy system.

4.3 Concurrent by-product reuse

In this paper, we study three independent companies involved in an industrial symbiosis network. We assume that there are two suppliers that have a similar industrial by-product, and a user that is able to use either by-product supply to substitute a raw material. In an industrial symbiosis network with multiple, concurrent suppliers, the limited by-product demand is a “scarce resource” that needs to be allocated to the different suppliers. Furthermore, by-product leftover (i.e. surplus) still needs to be disposed of. Figure 4.1 illustrates the system and the notation that we will introduce in the following.

ASSUMPTION 1. The industrial symbiosis network consists of concurrent suppliers with a total by-product supply that is more than the demand (D)¹, leading to a surplus ratio of by-products, ϕ . The total by-product supply is thus $q_1 + q_2 = D(1 + \phi)$.

¹For a by-product supply less than the demand, allocation would be trivial.

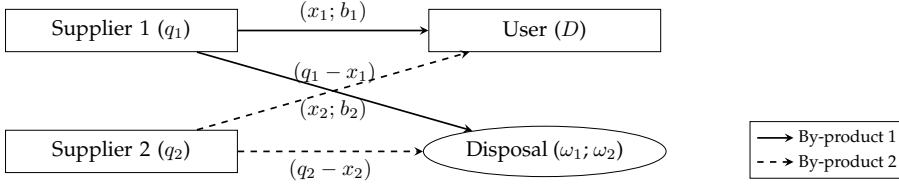


Figure 4.1: Overview of the industrial symbiosis network.

We denote the supply quantities of by-product available at the suppliers by q_1 and q_2 , and the demand quantity of the user by D . We use the variables x_i to denote a specific allocation of by-product from supplier i to the user. Due to the surplus in the system, we have $x_1 + x_2 = D$, $x_1 \leq q_1$, and $x_2 \leq q_2$. We also introduce supplier i 's proportion of the total supply r_i , leading to the following relationship:

$$q_i = r_i D(1 + \phi). \quad (4.1)$$

Note that in our two-supplier situation, a supplier's proportion to the total supply determines the other supplier's proportion that is $r_1 = 1 - r_2$.

After the allocation, supplier i still faces disposal costs for $q_i - x_i$ by-products, which for instance consists of the transportation and handling cost required in getting the by-product to a disposal site, as well as a possible disposal fee (e.g., landfill tax, incineration tax).

ASSUMPTION 2. Disposal costs are linear and proportional to the amount of by-products disposed, represented in a disposal cost factor ω_i for each unit of by-product disposed. Without by-product reuse in the industrial symbiosis network, supplier i faces the following disposal costs:

$$a_i = \omega_i q_i. \quad (4.2)$$

The literature on allocation and fairness generally distinguishes between gain-based and loss-based approaches (Hougaard 2009), which we follow in our work. Generally, industrial symbiosis leads to direct economic gains by saving disposal and raw material costs. Reduced costs translate into extra profit, depending on the operational efficiency of the synergetic relationships. Operations related to industrial symbiosis include supply chain activities such as collection, transportation and treatment (Bansal and McKnight 2009). Moreover, by-product reuse requires additional setups, testing, and storage (Flapper et al. 2002), as well as coordination efforts (Zhu and Côté 2004). Different by-product supplier-buyer relationships can therefore have different cost profiles, depending on the operations and coordination efforts. In other words,

concurrent by-product synergies in an industrial symbiosis network are not always equally efficient.

ASSUMPTION 3. Operational costs of by-product reuse (β_i) are linear and proportional to the amount of by-product reused. Furthermore, the parameter b_i represents the operational efficiency, i.e. how operational costs relate to disposal costs: $b_i = \omega_i - \beta_i$, $b_i > 0$.

ASSUMPTION 4. Without loss of generality: $b_1 > b_2$, meaning that by-product reuse from supplier 1 is more efficient than from supplier 2.²

For the gain-based allocation approach, we consider the profit (i.e. cost saving) that is made by reusing by-products.

ASSUMPTION 5. The profit generated by reusing by-products from supplier i is a linear increasing function of the allocated supply x_i with slope b_i :

$$p_i = b_i x_i. \quad (4.3)$$

The above profit structure is relevant for all gain-based allocations, where the profit is made on the level of the synergetic relationship. For the loss-based approach, only costs need to be considered. Here, by-product reuse reduces disposal costs; however, the by-product surplus still needs to be disposed of. In our paper, we therefore consider the disposal costs of remaining by-products as the costs for the loss-based approach.

ASSUMPTION 6. The residual cost of supplier i is a linearly decreasing function of the allocated supply x_i with slope $-b_i$ and intercept a_i :

$$c_i = a_i - b_i x_i, \quad (4.4)$$

Within the framework described above, efficiency is achieved by either maximizing the total profits in the system or minimizing the total (residual) costs. These are expressed with objective functions (4.3) and (4.4):

$$P^*(x_i) = \max \sum_i p_i = \max \sum_i b_i x_i, \quad (4.5)$$

$$C^*(x_i) = \min \sum_i c_i = \min \left(\sum_i a_i - \sum_i b_i x_i \right). \quad (4.6)$$

However, the system efficiency resulting from (4.3) or (4.4) might not always be the best solution. It has the potential to make one of the concurrent suppliers less competitive, and might thereby negatively influence the

²For equal efficiencies, the system would not have a loss of efficiency due to the fairness consideration, and there would not be a price of fairness.

resilience achieved by having multiple suppliers. In this paper, we therefore specifically focus on fair allocation of economic gains (or losses).

ASSUMPTION 7. In concurrent by-product reuse in industrial symbiosis networks, fair allocation ensures collective economic incentives to assure long-term resilience.

With the abstract system depicted in Figure 4.1, we provide a simple model of the economic potential of concurrent by-product reuse in industrial symbiosis networks. We do however not explicitly consider possible payments between suppliers and the buyer; how exactly profits or costs are distributed among the symbiosis participants is out of the scope of this paper. We aim focus on the overall system behavior where we use the individual synergetic relationships as the unit of analysis. In the following, we use the specific supplier to identify the specific synergetic relationship in the industrial symbiosis network, since this is the key distinguishing feature. It should however be noted that the efficiency attributed to a supplier then also includes the operational and organizational relationship with the buyer.

4.4 Fairness in by-product reuse

Optimal efficiency in concurrent by-product reuse is achieved when the more efficient supplier is fully utilized. In equation (4.5) and (4.6), this implies $x_1 = \min(q_1, D)$ and, consequently, $x_2 = \min(D - q_1, 0)$.

PROPOSITION 7. In concurrent by-product reuse in industrial symbiosis networks, optimal performance is achieved when the more efficient supplier is fully utilized. In case of the gain- and loss-based approach this implies, respectively:

$$P^*(x_1, x_2) = b_1 \min(q_1, D) + b_2 \max(D - q_1, 0),$$

$$C^*(x_1, x_2) = a_1 + a_2 - b_1 \min(q_1, D) - b_2 \max(D - q_1, 0).$$

For the analysis of fairness, we selected various allocation strategies: one equality-based strategy and two proportionality-based strategies for both gain-based and loss-based approach (presented in Figure 4.2). First, we consider the most basic strategy of equal profits (costs). Secondly, we use a strategy based on the Nash standard of comparison, which is the percentage change in profit (cost) when it is allocated a small additional amount of supply. According to the principle of the Nash equilibrium, a reallocation of demand between two suppliers is justified if the resulting marginal benefit of one supplier is more than the resulting marginal detriment of the other supplier (see also Bertsimas et al. 2012). Finally, we consider the maximum potential profits

Gain-based approach →	Equal Profits Strategy (EPS)	Equal Marginal Profits Strategy (MPS)	Proportional Profits Strategy (PPS)
Loss-based approach →	Equal Costs Strategy (ECS)	Equal Marginal Costs Strategy (MCS)	Proportional Costs Strategy (PCS)

Figure 4.2: Fairness strategies identified in the literature and applied on the industrial symbiosis network.

(minimum potential costs) of the suppliers and based on these, we derive a proportional allocation that ensures that the proportion of the actual profits (costs) and the maximum profits (minimum costs) are equal.

The strategies ensure fair profits (costs) by constraining equilibria (i.e. fairness rule) in the allocation of by-product demand to the suppliers (x_1, x_2) in specific ways. In the following, we utilize the fact that $x_2 = D - x_1$ in combination with the respective fairness rules to derive the resulting optimal allocations (x_1^*, x_2^*) as well as the corresponding price of fairness.

4.4.1 Gain-based approach

One way to be fair is to ensure equally profitable by-product synergies. The *equal profit strategy* (EPS) has the following fairness rule:

$$b_1 x_1 = b_2 x_2. \quad (4.7)$$

The first row of Table 4.1 concludes the roots (x_1^*, x_2^*) and the feasible quantity ranges of the EPS; equal profits cannot be assured when the maximum profit of one supplier is less than the minimum profit of the other supplier.

The *equal marginal profit strategy* (MPS) focuses on the marginal profit of a synergy that is gained when a small amount ϵ of by-products is added to the already allocated amounts. The comparison of marginal profits resembles the Nash equilibrium also used by Bertsimas et al. (2011). The MPS ensures equilibrium between the marginal profits of the suppliers with the following fairness rule:

$$\frac{\epsilon b_1}{b_1 x_1} = \frac{\epsilon b_2}{b_2 x_2}. \quad (4.8)$$

The roots of the MPS are expressed in the second row of Table 4.1. Based on equation (4.8), the MPS ensures an equal allocation ($x_1 = x_2$) of half of the demand, which is only feasible if both suppliers can cover at least half of the demand.

Strategy	x_1^*	x_2^*	Feasible range
EPS	$\frac{b_2 D}{b_1 + b_2}$	$\frac{b_1 D}{b_1 + b_2}$	$q_1 \geq \frac{b_2 D}{b_1 + b_2}; q_2 \geq \frac{b_1 D}{b_1 + b_2}$
MPS	$\frac{D}{2}$	$\frac{D}{2}$	$q_1 \geq \frac{D}{2}; q_2 \geq \frac{D}{2}$
PPS	$\frac{q_1 D}{q_1 + q_2}$	$\frac{q_2 D}{q_1 + q_2}$	$q_1 < D; q_2 < D$
	$\frac{q_1 D}{q_1 + D}$	$\frac{D^2}{q_1 + D}$	$q_1 < D; q_2 \geq D$
	$\frac{D}{2}$	$\frac{D}{2}$	$q_1 \geq D; q_2 \geq D$
	$\frac{D^2}{q_2 + D}$	$\frac{q_2 D}{q_2 + D}$	$q_1 \geq D; q_2 < D$

Table 4.1: By-product allocation and feasibility of fairness strategies with gain-based approach

Finally, the *proportional profits strategy* (PPS) ensures that the ratio of the actual profit and the potential maximum profit is the same for both suppliers. The mathematical formulation of this fairness rule is the following:

$$\frac{b_1 x_1}{b_1 \min(q_1, D)} = \frac{b_2 x_2}{b_2 \min(q_2, D)}. \quad (4.9)$$

Unlike in the previous two strategies there is always an allocation that satisfies equation (4.9). On the other hand, the denominators of equation (4.9) depend on the relation between q_i and D . Accordingly, the PPS has four different pairs of roots (see Table 4.1).

4.4.2 Loss-based approach

Similar to the gain-based approach, we again distinguish three fairness strategies for the loss-based approach. The *equal costs strategy* (ECS) ensures that the residual costs of by-product leftovers are equal for both suppliers with the following fairness rule:

$$a_1 - b_1 x_1 = a_2 - b_2 x_2. \quad (4.10)$$

Table 4.2 presents the roots of equation (4.10). It is important that equal costs cannot be assured when the minimum cost of one supplier is more than the maximum cost of the other supplier.

The *equal marginal costs strategy* (MCS) applies the Nash standard of comparison similar to the MPS. Consequently, the MCS applies the following fairness rule:

$$\frac{\epsilon b_1}{a_1 - b_1 x_1} = \frac{\epsilon b_2}{a_2 - b_2 x_2}, \quad (4.11)$$

Strt.	x_1^*	x_2^*	Feasible range
ECS	$\frac{a_1+b_2D-a_2}{b_1+b_2};$	$\frac{a_2+b_1D-a_1}{b_1+b_2}$	$q_1 \geq \frac{a_1-a_2+b_2D}{b_1+b_2}$ $q_2 \geq \frac{a_2-a_1+b_1D}{b_1+b_2}$
MCS	$\frac{1}{2} * (\frac{a_1}{b_1} + D - \frac{a_2}{b_2});$	$\frac{1}{2} * (\frac{a_2}{b_2} + D - \frac{a_1}{b_1})$	$q_1 \geq \frac{a_1b_2-a_2b_1+b_1b_2D}{2b_1b_2}$ $q_2 \geq \frac{a_2b_1-a_1b_2+b_1b_2D}{2b_1b_2}$
PCS	$\frac{b_1q_1(a_2-b_2D)+a_1b_2(D-q_2)}{b_2(a_1-b_1(q_1+q_2))+a_2b_1}$	$\frac{a_2b_1(D-q_1)+b_2q_2(a_1-b_1D)}{b_2(a_1-b_1(q_1+q_2))+a_2b_1}$	$q_1 < D; q_2 < D$
	$\frac{b_1q_1(a_2-b_2D)}{b_2(a_1-b_1(D+q_1))+a_2b_1}$	$\frac{a_2b_1(q_1-D)+b_2D(b_1D-a_1)}{b_2(b_1(D+q_1)-a_1)-a_2b_1}$	$q_1 < D; q_2 \geq D$
	$\frac{(a_2-b_2D)Db_1}{a_2b_1+(a_1-2b_1D)b_2}$	$\frac{b_2(a_1-Db_1)D}{a_2b_1+(a_1-2b_1D)b_2}$	$q_1 \geq D; q_2 \geq D$
	$\frac{a_2b_1D+b_2(a_1(D-q_2)-b_1D^2)}{a_2b_1+b_2(a_1-b_1(D+q_2))}$	$\frac{b_2q_2(a_1-b_1D)}{a_2b_1+b_2(a_1-b_1(D+q_2))}$	$q_1 \geq D; q_2 < D$

Table 4.2: By-product allocation and feasibility of fairness strategies with loss-based approach

leading to the roots presented in Table 4.2. The MCS is infeasible when maximum marginal gain of one supplier is less than the minimum marginal loss of the other supplier.

Finally, the *proportional costs strategy* (PCS) ensures that the ratio of the actual residual cost and the potential minimum cost of both suppliers are equal. This equilibrium of the proportions is formulated with the following fairness rule:

$$\frac{a_1 - b_1x_1}{a_1 - b_1 \min(q_1, D)} = \frac{a_2 - b_2x_2}{a_2 - b_2 \min(q_2, D)}. \quad (4.12)$$

Like the PPS, the PCS always has feasible allocations presented in Table 4.2, again leading to four possible pairs of roots, depending on the relation between q_i and D .

4.4.3 Price of Fairness

The consideration of resilience and fairness leads to an efficiency loss, which is the price of fairness. More specifically, the overall efficiency of the industrial symbiosis network decreases when the less efficient supplier has a nonzero demand allocation while the more efficient supplier is not completely utilized.

PROPOSITION 8. *Concurrent by-product reuse in industrial symbiosis networks is subject to a price of fairness when $x_2 > 0$ while $x_1 < q_1$. The price of fairness is the efficiency loss in the system, which can be quantified with the expressions in Table 4.3.*

The determination of the price of fairness is based on $1 - \frac{P(x_1, x_2)}{P^*(x_1, x_2)}$ and $\frac{C(x_1, x_2)}{C^*(x_1, x_2)} - 1$ for gain- and loss-based fairness strategies, respectively. Note that the price of fairness has a different expression depending on $q_1 < D$ or $q_1 \geq D$.

	$\text{POF}_{\text{profit}}(x_1, x_2)$	$\text{POF}_{\text{cost}}(x_1, x_2)$
$q_1 < D$	$1 - \frac{b_1 x_1 + b_2 x_2}{b_1 q_1 + b_2 (D - q_1)}$	$\frac{a_1 + a_2 - b_1 x_1 - b_2 x_2}{a_1 + a_2 - b_1 q_1 - b_2 (D - q_1)} - 1$
$q_1 \geq D$	$1 - \frac{b_1 x_1 + b_2 x_2}{b_1 D}$	$\frac{a_1 + a_2 - b_1 x_1 - b_2 x_2}{a_1 + a_2 - b_1 D} - 1$

Table 4.3: The price of fairness of gain-based and loss-based fairness strategies.

The price of fairness is further specified by replacing the roots presented in Table 4.1 and 4.2 into the price of fairness equations in Table 4.3. The general price of fairness equations displayed in Table 4.3 already depend on q_1 . Consequently, the applicable ranges of the roots identified previously define further segments of the price of fairness functions.

PROPOSITION 9. *The price of fairness of strategies with gain-based approach is a composite function. Its segment domains are determined by the relationship between supply (q_1, q_2) and demand (D), as well as the feasibility constraints of the strategies. For the different strategies, the price of fairness is given in equation (4.13)-(4.15).*

PROPOSITION 10. *The price of fairness of strategies with loss-based approach is composite function. Its segment domains are determined by the relationship between supply (q_1, q_2) and demand (D), as well as the feasibility constraints of the strategies. For the different strategies, the price of fairness is given in equation (4.16)-(4.18).*

4.5 Numerical analysis of fairness strategies

In this section, we analyze the different fairness strategies listed in Figure 4.2, elaborating on the by-product allocations and the resulting price of fairness for different parameter scenarios. We first consider the gain-based strategies (EPS, MPS and PPS), followed by the loss-based strategies (ECS, MCS and PCS). To help generalization of the results, we use the supply proportions r_1 and r_2 as well as the total by-product surplus (ϕ) in the analysis instead of the absolute values (note that $r_2 = 1 - r_1$). We also analyze the sensitivity of the price of fairness to changes in the suppliers' operational efficiency (b_1, b_2) and disposal cost parameters (ω_1, ω_2).

$$POF^*_{\text{EPS}} = \begin{cases} 1 - \frac{2b_1b_2D}{(b_1+b_2)(b_1q_1+b_2(D-q_1))} & \text{if } \frac{b_2D}{b_1+b_2} \leq q_1 < D, q_2 \geq \frac{b_1D}{b_1+b_2}, \\ 1 - \frac{2b_2}{b_1+b_2} & \text{if } q_1 \geq D, q_2 \geq \frac{b_1D}{b_1+b_2}. \end{cases} \quad (4.13)$$

$$POF^*_{\text{MPS}} = \begin{cases} 1 - \frac{0.5(b_1+b_2)D}{b_1q_1+b_2(D-q_1)} & \text{if } \frac{D}{2} \leq q_1 < D, q_2 \geq \frac{D}{2}, \\ \frac{1}{2} - \frac{b_2}{2b_1} & \text{if } q_1 \geq D, q_2 \geq \frac{D}{2}. \end{cases} \quad (4.14)$$

$$POF^*_{\text{PPS}} = \begin{cases} \frac{q_1(b_1-b_2)(q_1+q_2-D)}{(q_1+q_2)(b_2D+b_1q_1-b_2q_1)} & \text{if } q_1, q_2 < D, \\ \frac{q_1^2(b_1-b_2)}{(q_1+D)(b_2D+b_1q_1-b_2q_1)} & \text{if } q_1 < D, q_2 \geq D, \\ \frac{1}{2} - \frac{b_2}{2b_1} & \text{if } q_1, q_2 \geq D, \\ \frac{q_2(b_1-b_2)}{b_1(q_2+D)} & \text{if } q_1 \geq D, q_2 < D, \end{cases} \quad (4.15)$$

$$POF^*_{\text{ECS}} = \begin{cases} \frac{2a_2b_1 + b_2(2a_1 - 2b_1D)}{(b_1 + b_2)(a_1 + a_2 - b_2D - b_1q_1 + b_2q_2)} - 1 & \text{if } \frac{a_1 - a_2 + b_2D}{b_1 + b_2} \leq q_1 < D, q_2 \geq \frac{a_2 - a_1 + b_1D}{b_1 + b_2} \\ \frac{2a_1b_2 + b_1(2a_2 - 2b_2D)}{(b_1 + b_2)(a_1 + a_2 - b_1D)} - 1 & \text{if } q_1 \geq D, q_2 \geq \frac{a_2 - a_1 + b_1D}{b_1 + b_2}. \end{cases} \quad (4.16)$$

$$POF^*_{\text{MCS}} = \begin{cases} \frac{(b_1 + b_2)(a_1b_2 + a_2b_1 - Db_1b_2)}{2b_1b_2(a_1 + a_2 - Db_2 - b_1q_1 + b_2q_1)} - 1 & \text{if } \frac{a_1b_2 - a_2b_1 + b_1b_2D}{2b_1b_2} \leq q_1 < D, q_2 \geq \frac{a_2b_1 - a_1b_2 + b_1b_2D}{2b_1b_2}, \\ \frac{(b_1 + b_2)(a_1b_2 + a_2b_1 - Db_1b_2)}{2b_1b_2(a_1 + a_2 - Db_1)} - 1 & \text{if } q_1 \geq D, q_2 \geq \frac{a_2b_1 - a_1b_2 + b_1b_2D}{2b_1b_2}. \end{cases} \quad (4.17)$$

$$POF^*_{\text{PCS}} = \begin{cases} \frac{b_2(b_1 - b_2)(a_1 - b_1q_1)(q_1 - D + q_2)}{(a_1b_2 + a_2b_1 - b_1b_2q_1 - b_1b_2q_2)(a_1 + a_2 - b_2D - b_1q_1 + b_2q_1)} & \text{if } q_1, q_2 < D, \\ \frac{b_2q_1(b_1 - b_2)(a_1 - b_1q_1)}{(a_1b_2 + a_2b_1 - b_1b_2q_1 - b_1b_2D)(a_1 + a_2 - b_2D - b_1q_1 + b_2q_1)} & \text{if } q_1 < D, q_2 > D, \\ \frac{b_2D(b_1 - b_2)(a_1 - Db_1)}{(a_1b_2 + a_2b_1 - 2b_1b_2D)(a_1 + a_2 - b_1D)} & \text{if } q_1, q_2 > D, \\ \frac{b_2q_2(b_1 - b_2)(a_1 - b_1D)}{(a_1 + a_2 - b_1D)(a_1b_2 + a_2b_1 - b_1b_2D - b_1b_2q_2)} & \text{if } q_1 > D, q_2 < D. \end{cases} \quad (4.18)$$

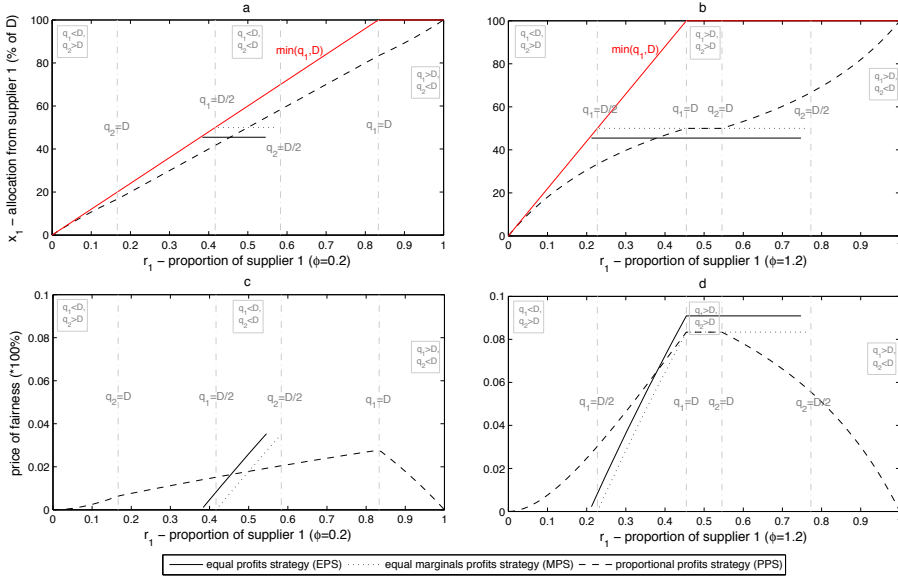


Figure 4.3: By-product allocation x_1 and the corresponding price of fairness with gain-based approach in relation to the proportion of supplier 1 r_1 . ($b_2 = 1$, $b_1 = 1.2$).

4.5.1 Price of fairness of gain-based strategies

Figures 4.3 (a,b) depict by-product allocations to supplier 1 (x_1) as a function of its supply proportion (r_1) for the gain-based fairness strategies. The figures present two surplus scenarios ($\phi = 0.2$ and $\phi = 1.2$), while the difference between the operational efficiency of the synergies is 20% ($b_1 = 1.2$, $b_2 = 1$).

Generally speaking, the potential maximum profit of the suppliers increases with their supply proportion. Accordingly, the allocation to supplier 1 (x_1) based on the PPS is increasing with the proportion of supplier 1 (Figure 4.3 (a)). Nevertheless, no additional profit is gained for the supply that exceeds the demand. Consequently, when $q_1, q_2 \geq D$, the PPS allocates a constant amount of half of the by-product demand to both suppliers (Figure 4.3 (b)). When $q_1 \geq D$ and $q_2 < D$, the allocation is increasing because the potential profit of supplier 2 becomes increasingly insignificant.

Contrary to the PPS, the other two strategies have limited feasibility and their allocation is constant (Figure 4.3 (a-b)). The MPS allocates half of the demand to both suppliers, which is only feasible while $q_1, q_2 \geq D/2$. On the other hand, the EPS slightly compensates the disadvantage of supplier 2. Therefore, the EPS generally allocates a bit more demand to supplier 2 than

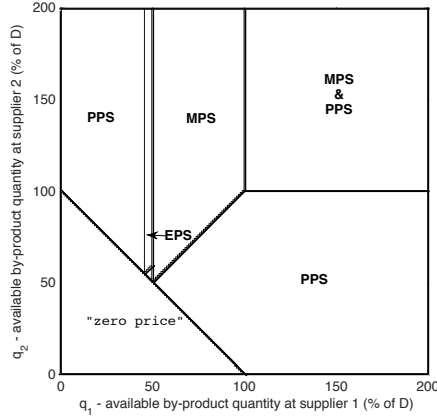


Figure 4.4: Minimum price ranges of gain-based fairness strategies as a function of by-product supply and demand. ($b_1 = 1.2, b_2 = 1$)

the MPS.

For a given supplier proportion, the distance between x_1 and $\min(q_1, D)$ in Figures 4.3 (a-b) leads to the price of fairness shown in Figures 4.3 (c-d). Consequently, the price of fairness for the PPS is increasing in r_1 as long as $q_1 < D$. Even though the allocation to supplier 1 is increasing with the r_1 in this range, the price of fairness is also increasing because the potential maximum profit of supplier 1 is increasing. On the other hand, when $q_1 \geq D$, the profit of supplier 1 is maximized and the price of fairness remains constant as long as $q_2 \geq D$ (Figure 4.3 (d)). Note that this plateau also corresponds to a constant allocation (Figure 4.3 (b)). Finally, when $q_1 \geq D$ and $q_2 < D$, the price of fairness resulting from the PPS starts to decrease.

The price of fairness resulting from the EPS and MPS is also increasing in r_1 as long as $q_1 < D$, and culminates in a plateau when $q_1 \geq D$. Here, the price of fairness also stays constant after $q_2 < D$.

4.5.2 Price of fairness of loss-based strategies

Our analysis of loss-based fairness strategies follows a structure similar to that of the previous section. Figures 4.5(a,b) depict by-product allocations to supplier 1 (x_1) as a function of r_1 . The figures again presents two surplus scenarios ($\phi = 0.2$ and $\phi = 1.2$), an efficiency difference between the suppliers of 20% ($b_1 = 1.2, b_2 = 1$), and disposal cost factor parameters of ($\omega_1 = \omega_2 = 2$).

Generally, as the supply proportion of a supplier increases, its potential disposal costs increase, while the potential disposal cost for the other supplier decrease. Additionally, proportional costs are subject to the potential

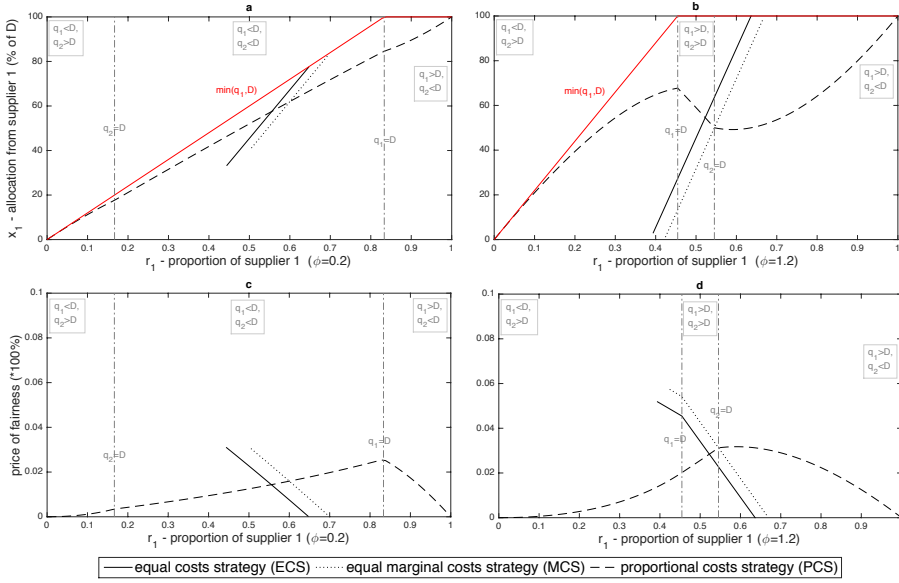


Figure 4.5: By-product allocation (x_1) and the resulting price of fairness with loss-based approach in relation to the proportion of supplier 1 (r_1). $b_1 = 1.2$, $b_2 = 1$, $\omega_1 = \omega_2 = 2$.

minimum costs of the suppliers, meaning that as the proportion of supplier 1 increases while $q_1 < D$, the potential minimum cost of supplier 1 increases with q_1 resulting in an increasing allocation (x_1) (Figure 4.5 (a)). After $q_1 > D$ the potential minimum cost of supplier 1 becomes subject to D while its disposal costs are still increasing resulting in a decreasing allocation (Figure 4.5 (b)). Nevertheless, when supplier 2 becomes relatively small, which implies $q_1 > D$ and $q_2 < D$, the cost of supplier 2 becomes insignificant and the demand allocation to supplier 1 is again increasing (Figures 4.5 (a-b)).

The ECS and MCS also follow the disposal cost of the suppliers and accordingly allocate monotonously increasing demand to supplier 1 (Figure 4.5 (a-b)). The efficiency difference between the synergies plays a role in case of the MCS, leading to slightly different feasibility limitations than in case of the ECS. Also, the MCS favors supplier 1 less than the ECS for a given supplier proportion.

The price of fairness corresponding to these scenarios is shown in Figures 4.5 (c-d). Again, the distance between x_1 and $\min(q_1, D)$ represents the price of fairness. Consequently, while $q_1 < D$, the price of fairness for the ECS and MCS is decreasing as the proportion of supplier 1 increases. Here, the price of fairness goes all the way down to zero while the allocation curves are getting

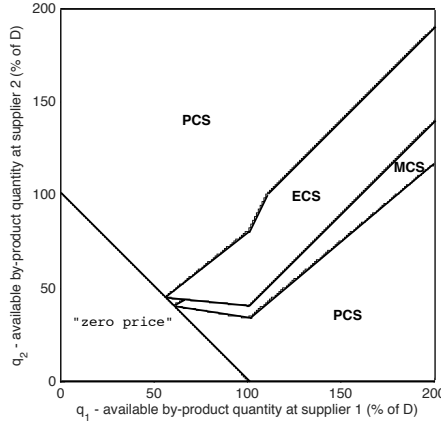


Figure 4.6: Minimum price ranges of loss-based fairness strategies in relation to by-product supply and demand. ($b_1 = 1.2, b_2 = 1, \omega_1 = \omega_2 = 2$)

closer to $\min(q_1, D)$. In contrast, the price of fairness of the PCS is increasing in this domain. After $q_1 \geq D$, the price of fairness for the ECS and MCS is further decreasing and the curves also become steeper due to the fact that the demand now limits the minimum cost of supplier 1 (Figure 4.5 (d)). In case of the PCS, the price of fairness further increases with the proportion of supplier 1 until the proportion of supplier 2 becomes insignificant. Consequently, the price of fairness peaks and then decreases for further increase in r_1 (Figures 4.5 (c-d)).

Figures 4.5(c-d) shows significant differences in the price of fairness between the PCS and the other two strategies. The MCS always has a higher price of fairness than the ECS. However, the feasible domain of the MCS also covers some larger proportions of supplier 1, meaning that the MCS has the lowest price of fairness in cases where the ECS is infeasible.

Figure 4.6 shows a comprehensive picture of the minimum price of fairness for any given supply combination. We can again ignore the range where $q_1 + q_2 \leq D$. As seen in Figure 4.5 (c-d), the feasibility range for ECS and MCS is limited, but they still lead to the lowest price of fairness for a reasonable range of supply proportions. In fact, the equal marginal costs strategy is likely to dominate the proportional costs strategy where the more efficient supplier has a slightly larger proportion of the total supply. Nevertheless, equal residual costs always results in a lower price of fairness than equal marginal costs. In a small range of supply proportions where q_2 is slightly larger than q_1 , the PCS leads to a lower price of fairness. For the remainder of the figure, only PCS is feasible, and inherently leads to the lowest price of fairness.

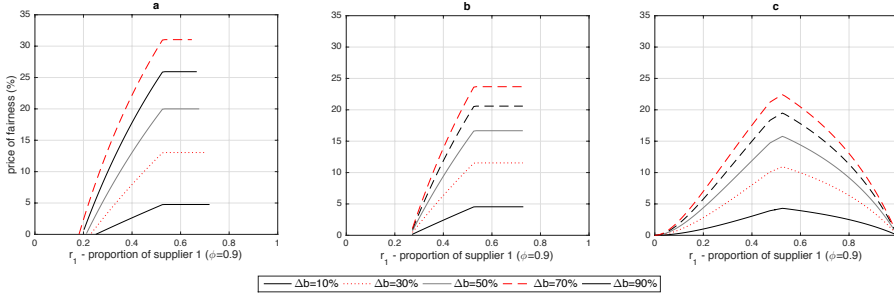


Figure 4.7: Sensitivity of the price of fairness in case of gain-based strategies (EPS, MPS and PPS from left to right) to differences in operational efficiency of the suppliers ($b_2 = 1$, b_1 is increasing)

4.5.3 Sensitivity analysis

In this section, we analyze the sensitivity of the price of fairness to differences in the operational efficiency and disposal cost parameters. Figure 4.7 depicts the sensitivity of gain-based fairness strategies for increasing efficiency differences Δb between the synergies. Here, b_1 is increasing while $b_2 = 1$. Figure 4.7 shows that increasing efficiency differences lead to an increasing price of fairness for all of the gain-based strategies. Furthermore, the price of fairness resulting from the EPS shows a stronger increase, since the allocation resulting from the EPS also changes with the efficiency difference.

In case of the MPS and PPS, allocation is independent from efficiency. Generally, increments in the price of fairness are proportional with the increments in the efficiency difference. This also means that the same b_1/b_2 ratio results in the same price of fairness. Finally, it is important to note that changes in efficiency do not influence the results presented in Figure 4.4.

Figure 4.8 depicts the sensitivity of loss-based fairness strategies to differences in efficiency b_i (first row) and differences in disposal cost ω_i (second row). For the differences in efficiency, the disposal costs are held constant at $\omega_1 = \omega_2 = 2$. In other words, the increasing efficiency means that supplier 1 recovers increasingly more of its initial by-product disposal cost. Consequently, the price of fairness resulting from the ECS and MCS is increasing as Δb increases (Figures 4.8 (a-b)). At the same time, the curves become steeper. Furthermore, while Δb increases, the feasible range of the ECS and MCS shifts towards larger proportions of supplier 1, decreasing the overlap between the ECS and MCS. Note that, accordingly, the situation of minimum price strategies in Figure 4.6 would change; the range in which MCS leads to the lowest price of fairness would get larger.

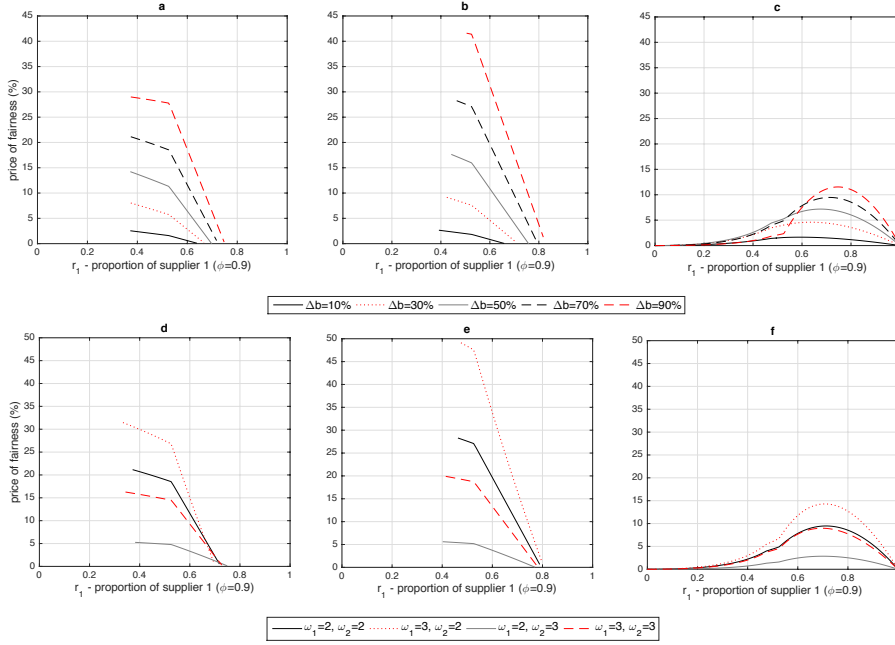


Figure 4.8: Sensitivity of the price of fairness in case of loss-based strategies (ECS, MCS and PCS from left to right) to changes in: to differences in operational efficiency of the suppliers ($b_2 = 1$, b_1 is increasing) - first row ; and disposal cost factor ($b_2 = 1$, $b_1 = 1.7$) - second row.

The price of fairness resulting from the PCS (Figure 4.8 (c)) is also increasing with Δb due to the generally increasing efficiency trade-off. However, the proportional strategy also takes into account the potential minimum cost of supplier 1. Therefore, when Δb , thus b_1 , is relatively high and q_1 is relatively low the price of fairness increases with a slower rate. Furthermore, as q_1 is increasing and Δb is decreasing this effect becomes insignificant relative to the efficiency trade-off.

Figure 4.8 (d-f) show the sensitivity results for the disposal cost. In general, when the disposal cost factor increases (ω_i), while the operational costs (β_i) remain unchanged, the actual cost saving resulting from by-product reuse increases. In other words, operational efficiency (b_i) increases. Note that this is also true with gain-based approach. Furthermore, if ω_1 increases, supplier 1 faces greater disposal costs and the price of fairness in the system also increases because a larger saving is sacrificed on behalf of the less efficient supplier. On the other hand, when ω_2 increases, the price of fairness decreases because the efficiency of supplier 2 improves. Furthermore, when ω_1 and ω_2 increase to the same extent, the relative difference between the operational ef-

Type of information	Fairness strategy					
	Gain-based			Loss-based		
	EPS	MPS	PPS	ECS	MCS	PCS
Demand	✓	✓	✓	✓	✓	✓
Supply			✓	✓	✓	✓
Efficiency and costs	✓			✓	✓	✓

Table 4.4: Information requirements of gain-based and loss-based fairness strategies

ficiencies of the suppliers decreases. Consequently, the price of fairness in the system decreases.

4.6 Discussion

In this section, we elaborate on the impact of the results presented in the previous section. We analyze the allocation strategies and their results from the perspective of the individual companies involved, as well as the perspective of a possible matchmaking broker. Such a brokerage function can be performed by the organizational unit that is often present in industrial symbiosis initiatives.

First of all, any kind of allocation strategy requires certain information about the suppliers. Arguably, a matchmaking broker might have difficulties obtaining information about operational efficiencies and cost structures. Furthermore, assessing efficiencies and calculating disposal costs is not always an option for the broker. Considering the nature of industrial symbiosis initiatives, in which a certain level of trust and willingness to collaborate can assumed to be present, information sharing barriers might not be as difficult to overcome as in regular supply chain relationships. Nevertheless, our results give insights in the information requirements of the different approaches, which could be decisive in the selection of a fairness strategy.

COROLLARY 1. *In by-product reuse in industrial symbiosis networks, fairness strategies have different information requirements with regards to determining fair allocations. The information requirements are shown in Table 4.4.*

Table 4.4 shows that the equal marginal and proportional profits strategies only require information on supply and demand quantities, even though they achieve a relatively low price of fairness in many situations. On the other

hand, the loss-based strategies also require information about the cost structures and the efficiencies of the suppliers.

During matchmaking, a broker can take the price of fairness resulting from an allocation into account, and assess whether it is worth sacrificing this efficiency to increase involvement in the industrial symbiosis and increase supply chain resilience in the synergy system. While keeping overall efficiency in perspective, economic engagement of the suppliers is the goal of the broker. In the long-term, however, the resilience would also be of interest for the individual suppliers.

Over time, reallocation might be required, since by-product supply and demand, and also cost and efficiency parameters can change. The different allocation strategies then lead to different reallocation, leading to specific incentives for the suppliers involved in the industrial symbiosis network in terms of adjusting their supply quantity, improving their efficiencies, or reducing some cost factors.

Taking a gain-based approach, a supplier might opt to increase available supply to leverage more profit from the synergy. In this case, the proportional profits strategy results in increasing allocation and profit for that supplier, at the expense of the other supplier. In other words, ramping supply up to a certain level pays off by employing this strategy. This feedback effect could induce competitive behavior between the suppliers. However, no additional allocation is granted when the available supply exceeds the demand. Note that allocation resulting from the other two strategies is not affected by increasing available supply.

COROLLARY 2. The proportional profits strategy increases allocation and profit for a supplier that increases its supply, thereby decreasing allocation and profit for the other supplier. As such, this strategy has the largest incentive to increase by-product quantities.

Following a loss-based approach, a supplier can opt to reduce its supply to lessen residual costs. Generally, when the equal or equal marginal costs strategy is employed, the overall industrial symbiosis network is better off if the less efficient supplier's supply is reduced. When the more efficient supplier's supply is reduced, then the proportional costs strategy results in a greater total cost reduction. The equal costs strategy yields equal cost reduction for both suppliers, but the equal marginal costs strategy always yields greater cost reduction for the more efficient supplier. The proportional costs strategy yields greater cost reduction for the supplier that reduces supply; moreover, if the supplier's supply exceeds the demand then this strategy adds extra costs to the other supplier.

COROLLARY 3. *The equal (and equal marginal) costs strategy splits cost savings resulting from reduced by-product surplus equally (nearly equally) between the suppliers. On the contrary, the proportional costs strategy keeps the cost savings for the supplier who reduced its supply, leading to a large incentive to reduce its by-product quantity.*

Improving efficiency — for example, by advancing technology — also affects profits and residual costs. The equal profits (costs) strategy shares the extra profit (cost savings) equally between the suppliers. Moreover, improving the economically less efficient supplier, or the supplier that has more available supply, yields greater collective profits or cost savings. Consequently, sharing technological advantage has a positive effect on the overall industrial symbiosis network when “equal” strategies employed. Note that allocations resulting from the equal marginal and proportional profits strategies are independent from efficiency. Thus, these strategies do not promote the sharing of technological advantage; they do however reward technological improvements for the individual suppliers. For the equal marginal costs strategy, residual costs increase for the supplier that improves efficiency, while assuring cost savings for the other supplier. Intuitively, this strategy therefore gives no incentives for technological improvements, instead requiring altruistic behavior. Finally, the proportional costs strategy assures most of the extra cost savings go to the supplier that made the efficiency improvement; moreover, this strategy adds extra costs to the other supplier if the available supply exceeds demand for any of the suppliers.

COROLLARY 4. *The equal profits and costs strategies promote sharing technological advantage by splitting the resulting extra benefits equally between the suppliers.*

Finally, a reason for reallocation could be an increase in by-product demand. Generally, this has a positive effect on the industrial symbiosis network and the extra demand is “fairly” allocated to the suppliers. By doing so, in case of proportional strategies, demand increase yields significantly greater extra profit or cost savings for the supplier with more supply.

Concurrent by-product reuse in industrial symbiosis networks is not always economically justified, especially when one relatively efficient supplier could cover all by-product demand. On the other hand, involving other suppliers in the network has benefits besides the previously discussed introduction of resilience. Actions that increase gains or reduce losses across the industrial symbiosis network improve the long-term financial and technological capabilities of companies in the regional industrial ecosystem. In this respect, fairness strategies result in more balanced benefits.

Type of action	Fairness strategy					
	Gain-based			Loss-based		
	EPS	MPS	PPS	ECS	MCS	PCS
Increase/decrease supply	—	—	I	C	C	I
Improve efficiency	C	I	I	C	A	I
Increase demand	C	C	I	C	C	I

Table 4.5: Characteristics of fairness strategies in terms of engaging companies in actions. C: collaborative, I: individualistic, A: altruistic, —: no effect.

COROLLARY 5. *In by-product synergy systems, fairness strategies engage companies either in collaborative, individualistic, or altruistic behavior. Table 4.5 summarizes these different behaviors for changing supply, demand, and efficiencies.*

Choosing the most suitable fairness strategy in regional ecosystems is an important initial effort of a matchmaking broker or a central organizational unit in an industrial symbiosis network. This effort may not only consider the price of fairness, but also consider how the employed strategy affects long-term collaboration issues such as sharing technological advantages, reducing by-product surplus, or increasing demand in the industrial ecosystem.

4.7 Conclusion and future work

Companies involved in by-product reuse in industrial symbiosis networks leverage a raw material substitute and avoid disposal costs generating system-wide competitive advantages. However, by-product synergies are normally subordinate to primary production operations. Consequently, a matchmaker brokering by-product reuse transactions can combine multiple, concurrent suppliers and/or buyers if that helps match by-product supply and demand and creates supply chain resilience. Furthermore, symbiotic relationships build on collective economic incentives, therefore, the assurance of fair but not necessarily equal benefits is one of the key challenges in resource allocation in industrial symbiosis networks.

In this paper, we developed a framework for concurrent by-product reuse in industrial symbiosis networks. We proposed fairness approaches to allocate demand to by-product suppliers in order to ensure collective economic benefits for the participating companies. Based on the literature, we identified three gain-based and three loss-based fairness strategies that we associated with the profits and costs that emerge in by-product synergies.

We derived the price of fairness resulting from the different “fair” allocations. Furthermore, we showed how the price of fairness changes in relation to the treatment costs and disposal costs of by-products, as well as to differences in the available by-product supply quantities. We found that strategies based on equal and equal marginal profits and costs generally motivate collaboration, such as reducing by-product surplus and sharing technological improvements within the industrial symbiosis network. On the other hand, strategies based on proportionality are found to reward individualistic behavior.

We also found that fairness strategies based on gain-based approaches require less information sharing compared with strategies based on loss-based approaches. Some of the gain-based strategies can however still lead to a relatively low price of fairness, while not requiring detailed information on cost structures. On the other hand, employing loss-based fairness strategies always requires information about by-product quantities and cost structures.

The results have clear managerial implications for companies involved in initiating or operating industrial symbiosis networks, as well as for match-making brokers and central organizational units in such networks. Since brokers normally aim to efficiently allocate by-product supply and demand, and create effective, resilient collaborative industrial networks, our results also contribute to regional ecosystem development.

Similar to situations with concurrent suppliers, concurrent by-product users would also increase resilience in industrial symbiosis. When there is limited by-product supply and more than one by-product user with excess demand, fairness strategies could also be relevant for allocation. In fact, an industrial symbiosis network of one supplier and two buyers would leverage the cost savings of avoiding raw material procurement, while still facing residual procurement costs due to a possible by-product shortage. Consequently, the gain- and loss-based approaches and the profit and cost structures of this paper will be applicable in a one supplier two buyers setup. This strengthens the generality of our results regarding the price of fairness in concurrent by-product synergy systems.

One of the limitations of our study is the basic industrial symbiosis network structure. When more suppliers would be involved, allocation would be more complex. However, the fairness strategies introduced in this paper would still be relevant. Intuitively, increasing the number of suppliers with low efficiencies would increase the price of fairness. Furthermore, the information requirements and the engagement incentives of the strategies we identified would still hold in larger systems.

Another limitation is that the price of fairness is only based on the disposal

costs and the operational efficiency. Even though our definition of operational efficiency can cover many differences between the suppliers, we did not include the potential increase in transaction costs resulting from managing an increased supplier base. Nevertheless, since industrial symbiosis builds on trust and information sharing in long-term relationships, transaction costs are arguably reduced to a minimum.

Based on the above-mentioned limitations, a future extension of this work would be to further elaborate on collaborative allocations and analyze the price of fairness in situations with more than two by-product suppliers or more than one user. Furthermore, since resource efficiency and environmental considerations are key drivers of industrial symbiosis initiatives, another relevant topic for further study would be the environmental impacts of different fairness strategies.

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CHAPTER 5

Conclusions

This thesis makes a contribution to research in sustainable supply chain management by elaborating on the industrial symbiosis phenomenon. Industrial symbiosis networks are a collaborative effort to sustainability and are a form of closed-loop supply chains. Industrial symbiosis is characterized by a supply chain reconfiguration that connects undesired production outputs to material intake resulting in new material flows while eliminating others. The resulting network of relationships emphasizes synergistic relations, community, and collaboration within geographical proximity. Industrial symbiosis contributes to regional sustainable development efforts, involving competitiveness and an efficient use of natural resources.

There is ample research on industrial symbiosis, but not from an operations and supply chain management perspective, even though many related challenges can be identified. This thesis takes this perspective and acquires new knowledge through focusing on its key characteristics. The thesis thereby grounds industrial symbiosis in operations and supply chain management theory, and it provides a basis for the improved organization and operation of industrial symbiosis networks.

5.1 Summary of findings

The key characteristics of industrial symbiosis networks are reflected in the collaborative effort of the participants to sustainability and in the competitive advantages that synergistic relations offer. This thesis elaborates on both of these characteristics; furthermore, it connects them by focusing on the trade-

off between collaborative effort and individual economic interests. Consequently, three pairs of research questions are answered. The first pair of questions deal with the collaborative effort to sustainability in industrial symbiosis networks:

RQ1a — How do companies in industrial symbiosis pursue the triple bottom line of sustainability?

RQ1b — What are the supply chain collaboration challenges that affect the sustainability performance of industrial symbiosis networks?

In general, the triple bottom line of sustainability refers to profit, planet, and people related performance. Furthermore, concerning these drivers, organizational, governmental, and community stakeholders of the companies create pressure and incentives to improve performance. As a result, collaborative effort manifests in geographical proximity in a form of industrial symbiosis. Chapter 2 of this thesis looks at fifteen industrial symbiosis networks reported on by case studies published in academic journals.

By looking at examples worldwide, it is clear that industrial symbiosis means business concerning profitability. In a synergistic transaction, including a supplier and a buyer, it is necessary that both parties reduce costs or gain extra revenue as opposed to a system without that synergy. However, synergies do not come into existence or come to an end if in the long-term its associated costs offset its benefits, or a better alternative arises.

Furthermore, from the case studies it turns out that industrial symbiosis is typically driven by regulatory and financial instruments that emphasize environmental performance. In fact, emission regulations and waste disposal costs were found as the main reason for initiating synergistic transactions. Indeed, industrial symbiosis simultaneously avoids disposal and reduces part of the upstream supply chain activities associated with the production of raw materials. However, companies that constitute supply and demand for wastes and by-products may still rely on unsustainable technologies and/or toxic materials undermining the sustainability effort in industrial symbiosis networks. In fact, many industrial symbiosis examples include power plants burning coal and refineries processing oil and natural gas.

Finally, from the case studies it turns out that companies in industrial symbiosis integrate the perspectives of community stakeholders into their environmental strategy. Furthermore, industrial symbiosis often entails new operations that create employment opportunities.

In terms of the collaborative effort to sustainability, industrial symbiosis networks face challenges attributed to supply chain integration and coordi-

nation. Chapter 2 identifies specific challenges concerning organizational and operational aspects of collaboration. As far as sustainability performance is concerned, synergies have to emphasize non-hazardous material flows between environmentally sustainable processes. Furthermore, mutual economic incentives need to be sustained for long-term cooperation by coordinating cost, benefit, and risk sharing in the network. From the case studies it turns out that often a dedicated organizational unit takes care of the tasks related to coordination. However, establishing an organizational unit is a challenge. It requires a communication platform that integrates local industrial communities and authorities. Additionally, members of the organizational unit have to engage a diverse set of stakeholders in social networking and in local problem solving, and effectively coordinate transactions.

From an operational perspective, industrial symbiosis networks often require dedicated infrastructure, such as a pipeline network that transports steam, or transportation devices and warehouse facilities that collect, store, and deliver wastes and by-products. An efficient infrastructure increases the geographical range of industrial symbiosis networks by making potential synergies at larger distances economically feasible. However, implementing such system needs investment; furthermore, integrating by-product treatment, storage, and reuse into operations is difficult when companies prioritize their core operations.

Once industrial symbiosis is operational, it leads to additional challenges. In fact, it is likely to have mismatch between by-product supply and demand because the market mechanisms that generate them are usually independent. Furthermore, because by-products are side effects of production their quality and quantity bear uncertainty, which can negatively affect industrial symbiosis. This leads to coordination challenges. Consequently, it is likely that original and by-product materials need to be combined in procurement and production planning decisions. Furthermore, matching by-product supply and demand, and also securing continuous and stable quality and quantity may only be ensured on a broader market, involving more parties. However, these challenges come with additional transaction and operational costs, and increase the complexity of coordination.

In addition to the physical infrastructure, an informational infrastructure that provides aggregated and temporal data on material flows contributes to industrial symbiosis networks. Nevertheless, the required data is not always available, and companies can be reluctant to share production-related information.

After identifying challenges related to collaboration, the thesis elaborates

on the other key characteristic of industrial symbiosis networks. The second pair of research questions focus on competitiveness in industrial symbiosis:

RQ2a — What are the key capabilities and resources that firms participating in industrial symbiosis rely on?

RQ2b — How is competitive advantage in industrial symbiosis networks obtained based on these capabilities and resources?

Chapter 3 of this thesis grounds industrial symbiosis in the theory of competitiveness. The thesis analyzes eight industrial symbiosis networks using the resource-based view of competitive advantage. More specifically, the view includes the natural-resource-based view of the firm, the relational view of inter-organizational cooperations, and the contingent resource-based view of proactive corporate environmental strategy. Accordingly, three dimensions of organizational capabilities and resources are identified.

On the first dimension, the proactive environmental stance of individual firms was found to be essential. In fact, firms need to be aware of inputs and outputs of other industries to recognize symbiosis opportunities. Based on the case studies, it was concluded that firms also draw on dynamic organizational capabilities that allow supply chain reconfiguration and integration, as well as on life cycle thinking and proactive stakeholder management. Furthermore, it was concluded that stable, continuous and reliable by-product supply and demand are the central resources in industrial symbiosis.

On the relational dimension, industrial symbiosis entails strategic alliances and network embeddedness. It was found that firms draw on experience in complementary strategic alliances and in the efficient management of interdependencies, as well as on symbiosis-specific knowledge transfer routines. Furthermore, firms in industrial symbiosis networks leverage familiarity and emphasize collective problems embedded in their community. However, in cases where stakeholder involvement or network embeddedness was lacking the development of industrial symbiosis was hindered.

On the dimension of contingencies, the general business environment, including institutionalization and an organizational unit, was identified as a vital part of industrial symbiosis networks. In fact, institutionalization and the organizational unit were found closely related. In the analyzed industrial symbiosis cases, institutionalization created a business context that supported industrial symbiosis with regulatory and financial instruments. However, obstructive legislation halted practical implementation. Furthermore, the organizational unit reduced uncertainty and complexity concerning businesses by providing symbiosis-specific information, mechanisms that ensure collective

benefits, and by effectively coordinating transactions.

As far as competitiveness is concerned, sustained competitive advantage in industrial symbiosis networks is attributed to two general conditions. First, industrial symbiosis creates value by increasing productivity, reducing costs, generating revenue, and/or mitigating risk attributed to natural resource scarcities based on idiosyncratic supply chain relations. Second, industrial symbiosis is difficult to imitate due to a combination of capabilities and resources that feed into operations and supply chain management.

Acknowledging the fact that industrial symbiosis networks develop gradually, the thesis illustrates how competitive advantage is obtained throughout the initiation and progression of networks. It argues that firms that systematically aim to turn undesired production outputs into a resource and invest in learning about material flows in their surroundings obtain advantage in initiating industrial symbiosis. Additionally, in a business environment that supports the reuse of by-products with financial and regulatory instruments, and where transparency and institutionalized forms communication and cooperation are present, firms are more likely to initiate industrial symbiosis. However, synergistic transactions based on high-quality by-products and with matching supply and demand are more competitive. Furthermore, firms that possess the necessary financial resources and managerial capabilities to reconfigure their supply chain and to engage other firms in industrial symbiosis obtain competitive advantage.

The progression of industrial symbiosis involves an increased emphasis on sustainability, on diversity in terms of materials and firms involved, and on supply chain resilience concerning redundancy; however, it implies increasing network complexity. It is suggested that firms that secure their exclusive access to by-product supply or demand, as well as increase the proportion of synergy-sensitive resources and/or operations in synergistic relations obtain competitive advantage. In addition, partners that emphasize symbiosis-specific knowledge sharing routines are more competitive because they are more likely to find new synergistic opportunities. Furthermore, it is suggested that firms have advantage in increasing the number of synergies when they have effective coordination mechanisms in place. Based on the analyzed cases, however, it seems that complex industrial symbiosis networks are coordinated by an organizational unit. It is concluded that to facilitate progress, the organizational unit needs a vision and performance objectives concerning low impact technologies and sustainable development. Furthermore, an organizational unit that is able to ensure collective economic incentives, and broaden the market of by-products contributes to the competitiveness of the

industrial symbiosis network.

Finally, the thesis elaborates on collective economic incentives in industrial symbiosis networks with multiple, concurrent by-product suppliers. In general, such redundancy is an operational strategy to increase resiliency by improving the stability, reliability, and continuity of supply. In industrial symbiosis, this however leads to allocation problems, in which limited by-product demand has to be allocated to the suppliers. Considering a collective distribution of costs and benefits, the demand allocation needs to include fairness considerations. However, fairness normally comes with a cost, which is the trade-off for emphasizing collective gains or losses instead of an economically optimal allocation. Chapter 4 of this thesis focuses on fair allocation strategies in industrial symbiosis networks by answering the following pair of research questions:

RQ3a — How can the price of fairness be measured in industrial symbiosis networks?

RQ3b — How do different fairness approaches influence collaboration in industrial symbiosis networks?

Chapter 4 introduces a minimal formal model of an industrial symbiosis network, including two suppliers and one buyer, which allows to easily derive by-product allocations and the price of fairness for allocation strategies with different fairness consideration. The analysis includes two approaches to allocation. The gain-based approach considers the economic savings that are made by avoiding the disposal costs. The loss-based approach, on the contrary, considers the residual costs the suppliers face for disposing their by-product surplus. A central assumption is that the operational cost structures of the two suppliers are not equal. Consequently, allocating demand to the less efficient supplier while the more efficient supplier's supply is not fully utilized implies a price of fairness. This price of fairness can be quantified and depends on how fairness is defined. The thesis offers three definitions of fair allocation that are applicable for both gain- and loss-based approaches. The most basic option to include fairness is to ensure equal gains (losses) for both suppliers. A second option is based on the Nash standard of comparison, which is the percentage change in gains (losses) when it is allocated a small additional amount of supply. This allocation ensures equal marginal gains (losses) to the suppliers. Finally, a third option is to ensure that the proportion of the actual gains (losses) and the potential maximum gains (minimum losses) of the suppliers are equal. The thesis elaborates on the resulting six allocation strategies in terms their price of fairness, their information sharing

requirements, and their impact on collaborative behaviour.

After numerical analysis it is concluded that the price of fairness depends on circumstances, including the amount of available supplies at the individual suppliers, the total surplus in the system, and the efficiency difference between suppliers. Furthermore, the allocation strategy with the lowest price of fairness depends on a combination of circumstances. In case of the gain-based approaches, it was found that typically a low price is achieved when equal by-product demands are allocated to the suppliers; however, when the more efficient supplier has more available supplies, the proportional strategy results in the lowest price of fairness. In case of the loss-based approaches, the results are more subtle, but in general, the proportional strategy results in the lowest price of fairness. However, when the suppliers have close to equal amounts of available supplies, then the equal and equal marginal strategies lead to a lower price of fairness.

In the thesis, it is argued that fairness should be managed by the organizational unit of the industrial symbiosis network. A central broker can coordinate a broader by-product market that will increase resilience in the supply-demand network. However, to ensure fairness, the broker needs information about the circumstances in the network. It is found that the information requirements of the fairness strategies are different. In fact, the equal marginal gains strategy only requires information about the demand quantity because it allocates equal demand between the suppliers. The proportional gains strategy requires additional information about the available supplies, and the equal gains strategy also requires additional information about the costs structures of the suppliers. In general, the loss-based fairness strategies require more information, including demand quantities, supply quantities, and information about the supplier's costs structures. Consequently, gain-based fairness is easier to implement in industrial symbiosis networks.

Furthermore, it is argued that the broker considers how fairness strategies affect the collaborative effort or promote competitive behaviour in the network. It was demonstrated that the proportional gains strategy increases allocation and gains for the supplier that increases its available supply, thereby decreasing the allocation and gains for the other supplier. Similarly, the proportional losses strategy keeps the cost savings for the supplier that reduces its available supplies. Consequently, strategies based on proportionality introduce incentives to behave individualistically, thus promoting competition in the network. On the contrary, the equal and marginal losses strategies split the cost savings resulting from reduced by-product surplus nearly equally between the suppliers. Furthermore, the strategies based on equal gains and

losses split the extra benefits resulting from efficiency improvements, thereby encouraging the sharing of technological developments within the network. Consequently, strategies based on equality and marginal equality introduce incentives for joint action and knowledge sharing, thus promoting collaboration. Nevertheless, ensuring collaborative incentives and keeping the additional costs of redundancy at an acceptable level remains a challenge.

5.2 Future research directions

Industrial symbiosis is an important part of the resource efficiency framework suggested in European policy, and it is recognized as a key feature of circular material flows in industrial systems. The European action plan for circular economy will inevitably strongly increase the focus on the use of waste flows as replacement of virgin resources and hence the focus in the coming years on industrial symbiosis.

Fully circular material flows, however, are seldom observed in practice. In fact, most of the industrial symbiosis networks worldwide are not circular; they are part of larger industrial systems that still rely on nonrenewable resources and/or generate environmental hazards. One reason for this is that to achieve circular material flows, the design of products in terms of materials used and product architecture might have to be changed. Nevertheless, in a future where products are designed for a circular economy, it is likely that material flows across supply chains become increasingly relevant, and thus industrial symbiosis will be more prominent.

It is important to consider that closed-loop supply chain management operates on two distinct dimensions. On the one hand, it deals with a product flow dimension along supply chains, manifesting forward and reverse flows of products and materials. On the other hand, it deals with material flows across supply chains, within geographical proximity, manifesting relationships outside the core businesses of firms. This second dimension defines a distinct area for industrial symbiosis research. However, from a managerial perspective, it is important to know how far those geographical boundaries can be stretched. And more importantly, what the limiting conditions for increasing the radius of material flows in industrial symbiosis networks are. To some extent, these conditions are economic considerations and can be overcome with efficient organization and logistics. Increasing environmental pressure and legislation is also likely to increase the willingness to invest in symbiotic relationships and thus extend the geographical boundaries. However, there might be a spatial limit outside of which community ties are not

strong enough to form industrial symbiosis.

In most of the examples of industrial symbiosis networks large companies with stable and continuous supply and demand constitute dyadic synergistic transactions. This also leads to further research questions. Is industrial symbiosis only a strategy for large companies; and if not, how can small flows of by-products be organized into a network? It could be that industrial symbiosis manifests spontaneously and only works well in a form of dyadic transactions; and it is likely that including small and medium-sized companies will require an organizational unit or broker in order to match supply and demand. However, increasing the number of participants in the network increases complexity and transaction costs, including the cost of coordination and risk attributed to supply and demand uncertainty, even though it might also increase network resiliency. Consequently, future research in this direction should go beyond dyadic relations in industrial symbiosis networks. Furthermore, moving towards circular economy will increase the need for systematic approaches to the optimization of supply chains in an industrial symbiosis context.

Even though examples of industrial systems operating with fully circular material flows might be developed in the near future, it is likely that wastes and by-products will remain secondary for companies as their priority is on their core production. In a circular system, however, the replenishment rate of wastes and by-products would affect the rate of production. Furthermore, increasing or decreasing the intake or output of one production entity has an effect and depends on the other entities because of material surplus or shortage. Consequently, in a circular system, individual companies will become more interdependent compared with traditional supply chains.

From a managerial point of view, it is interesting to further elaborate on the mechanisms that affect material supply and demand and the sustainability performance in circular economies; as part of this, an operations and supply chain management perspective on industrial symbiosis can provide useful support. Further research can extend the theoretical basis provided in this thesis, and provide additional empirical and analytical foundations for resource efficiency and circular material flows.

Empirical research is supposed to uncover and study cases of circular economies based on synergistic relations, and for example, test the propositions presented in this thesis. Furthermore, analytical work could be performed to provide decision support regarding the optimal dimensions of circular economies, including production and consumption capacities and geographical boundaries. This type of research could also support the development towards a circular economy.

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This thesis grounds industrial symbiosis in operations management and supply chain management theory. Specifically, the thesis elaborates on the collaborative and competitive characteristics of industrial symbiosis. First, it considers the supply chain integration and coordination challenges that appear in industrial symbiosis networks, on both organizational and operational level. Secondly, the thesis discusses the organizational capabilities and resources relevant for competitiveness on three dimensions: the level of the firm, the network, and the business environment. Finally, the thesis elaborates on supply chain resiliency based on a formal model applying fairness considerations to allocate resources between multiple concurrent suppliers. Overall, the thesis provides a basis for the improved organization and operation of industrial symbiosis networks.

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